NS125: Final Project

Research Proposal

Understanding the Mass Segregation Mechanism in Open Star Cluster

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Introduction

Stars are often formed in a cluster, thus understanding the initial condition of star clusters works as a key to understand the star formation. Many star clusters show mass segregation– most massive stars stay in the center and low-mass stars at the outskirts. One important question is how did this segregation happen? Is it primordial, i.e. the cluster forms in this way or is it due to cluster dynamics? Due to the energy equipartition process, stars of different mass exchange energy via two-body interaction, which could lead to mass segregation (Fragione et al, 2018). Again other theoretical models support primordial segregation (Mattern et al, 2018).

Observational evidence is few in this debate as it requires finding all cluster members and estimating their mass. Without very precise measurements, we could not confidently find the fainter low-mass members on the outskirts. Very recently GAIA mission (Gaia Collaboration, 2018) provides very precise astrometric data (position, velocity across sky plane etc.), which opens up a new era in open cluster studies (Dias et al., 2021; Cantat-Gaudin et al., 2020). Thus using a more complete and reliable dataset, we can now look for observational evidence for the mass segregation mechanism.

Existing Literature

There are three methods in the past literature to measure mass segregation in an open cluster. For all of them, first, we need to estimate the mass of the members from their photometric data. We fit the member data (precisely their absolute magnitude and the color (difference in magnitudes in different bands)) to a theoretical isochrone (i.e., HR diagram or CMD) considering the distance and extinction of the cluster. For example, Hasan & Hasan (2011) used the synthetic isochrones from Girardi et al. (2002). After fitting, each point of the theoretical isochrones provides corresponding mass estimates. The uncertainty of the mass will depend on the uncertainties of the distance and extinction (Pavlík et al. 2019), which in turn depend on data preciseness.

The least common and simplest method for determining mass segregation is considering the average mass in the different annular regions around the cluster center. Pang et al. (2020) suggested no mass segregation in NGC 2232 following this approach. One major drawback is that a few massive stars can skew the mean of the all star mass. Thus using the median is a better approach.

The most popular and oldest method compares the slope of the mass function in different cluster regions (Sabbi et al., 2008; Pang et al., 2013, etc.). The mass function shows the number density of the stars for different mass bins (i.e., between a range of masses). It is a power law, which becomes a linear relation in logarithmic scale with the slope denoted by α. In a mass-segregated cluster, the slope in the outer region should be steeper (low mass stars increase and high mass stars decrease) compared to the central region. Authors often only visually present how slope decreases across the radius and explain qualitatively. Pang et al. (2013) showed the slope in six different annular regions in NGC 3603 cluster and how they decrease to support mass segregation. Similarly, Tang et al. (2018) showed mass segregation in Coma Berenices and Hasan & Hasan (2011) in nine clusters. The mass function provides a complete idea on the structure of the clusters. However, one limitation is the lack of a standard quantitative metric to determine the degree of mass-segregation. Also, the choice of cluster center, mass bins, and different regions can affect the mass function, therefore need to be justified..

The last and the most recent method is developed by Allison et al, 2009b using the minimum spanning tree (MST) method. It compares the average distance among N most massive members ($l_{massive}$) to the randomly chosen N members from the cluster. For the average member distance, 100 or more set of N random stars are chosen with a mean and standard deviation of $< l_{normal} >$and σ_{normal}. Then the mass segregation ratio is defined by,

$$\Lambda_{MSR} = \frac{<l_{normal}>}{l_{massive}} \pm \frac{\sigma_{normal}}{l_{massive}}$$

As a quantitative measurement, it allows us to find the degree (or strength) of the mass segregation as well as to find how many stars are segregated. Pang et al. (2013) and Zhang et al. (2020) used this method to find mass segregation in NGC 3603 and Blanco 1 respectively. Later Pang et al. 2021 showed that it can also be applied using the 3D position of the stars.

Olczak et al. (2011) modified it to incorporate a geometric mean instead of an arithmetic mean to reduce any outlier effect. Another limitation is that we need to estimate the exact mass of every single star, which often introduces more uncertainties. In the mass function method, we could just take all the stars in a specific position of the CMD and estimate the mass within the range of a mass bin.

Now regarding the observational evidence of the mass-segregation mechanism, we can find different conclusions from different papers. Haghi et al, 2015 and Zonoozi et al, 2017 found evidence of primordial mass segregation in the globular cluster of the milky way. But for open clusters, most observational evidence came only from the active star-forming regions, which are potential future open clusters. Lane et al (2016) and Plunkett et al (2018) found mass segregation in the star-forming regions in the Orion A molecular cloud region and Serpens South cloud. Similarly, Dib & Henning (2018) analyzed several nearby and distant star-forming regions and found mild to significant mass segregation.

Among the younger clusters, Hasan & Hasan (2011) showed mass segregation in NGC1893 and IC1805, both of which are too young to be dynamically mass segregated. Thus they argued that it might be born as mass segregation. Similarly, Pavlik et al., 2018 showed that after considering extinction carefully the observed data of the Orion Nebula Cluster (ONC) fit the initial mass segregation simulation better than the dynamic segregation. They further suggested that after 3.3 times of the relaxation time, an initially mass segregated and a non-mass segregated cluster become almost identical to distinguish by observed data. Relaxation time is when, due to regular energy exchange, all the stars lose the memory of their initial velocity. This could be one reason why we have less observed evidence of primordial mass segregation as only a relatively young cluster could show such evidence.

On the other hand, Hillenbrand & Hartmann (1998) Allison et al. (2009a) argued that even the younger mass segregation may be a result of a violent and chaotic two-body relaxation. (Hillenbrand & Hartmann 1998; Allison et al. 2009a). Allison et al. (2009a) derived the time for relaxation and time when a certain mass limit will be segregated in an open cluster. Then using simulated data and MST method, they showed why young clusters like ONC are mass segregated only to a certain limit. Tarricq et al (2022) applied the MST method on 389 local open clusters and found no common trend of mass segregation on Age. But they found that the sample of clusters, that have more than 10% of mass segregated stars, are relatively older than the other clusters. Thus they argued that over time the clusters will be more mass segregated due to the dynamical interaction.

Overall, we can see that each of the three methods of mass segregation has its advantages and limitations. But the MST method, by the virtue of being quantitative, allows more flexibility to compare mass segregation among different clusters. The mass function also provides useful insights on cluster structure, but we should come up with quantitative measurement and justify our choice of cluster radius, and the radius of the different annular regions.

One limitation in all the papers before GAIA data (2018) is the lack of precise measurement of stars' position and velocity. This might result in not considering many low-mass stars from the outskirts of the open clusters. Also as the relaxation time depends on the total number of stars and the velocity dispersion, it will also likely change after considering the GAIA data. As GAIA now provides a more robust, reliable, and complete open star members catalog, we could try to look into the mass segregation in a more diverse open star dataset to search for evidence for primordial mass segregation.

Data Exploration

Dias et al. (2021) catalogs the updated parameters of 1743 open clusters including their age, radial velocity, distance etc. Cantat-Gaudin et al., (2020) lists all the confident members (a total of 4,01,448 members from 1481 open clusters) of the open clusters along with their basic astrometric (position, velocity, etc.) and photometric data (magnitude, color). In the preliminary data analysis, I want to understand if we can find any noticeable difference between old and young clusters in terms of the mass function slope difference in the inner and outer regions.

I made some assumptions to simplify my analysis. First, instead of fitting an isochrone and getting the mass function, I plotted the magnitude function (or luminous function). Here I expressed the number density of the stars for different bins of absolute magnitude instead of bins of mass. The magnitude is proportional to the log(brightness) and log(brightness) is proportional to the log(mass) (as for main sequence stars mass-luminous relationship is $L \propto M^{\alpha}$; $\alpha \sim 3.5$, thus $log(L) \propto log(M)$). So if I expressed log(number density) as a function of magnitude, then it will be proportional to the expression log(number density) vs log(M), i.e. the mass function.

Secondly, for separating between the inner and outer region, I just simply took the half of the maximum distance from the cluster center. In the original research, we should more strongly justify our radius choice to avoid any subjectivity bias or reduce any uncertainty.

First we randomly chose three old (log(age) > 8) and young (log(age) < 7.5) open cluster samples. Then we divide them into inner and outer regions. For both regions, I calculated the number of stars in specific magnitude bins, plotted them logarithmically and found the slope of the best fit line (with its standard error) as shown in Fig 1. From there I calculated the difference of outer and inner slope and plotted them as a function of log(age) (Fig 2). The error of the difference of slope, $\Delta(slope_1 - slope_2) = np.sqrt(\,\Delta slope_1^{\,2} + \,\Delta slope_2^{\,2}\,)$

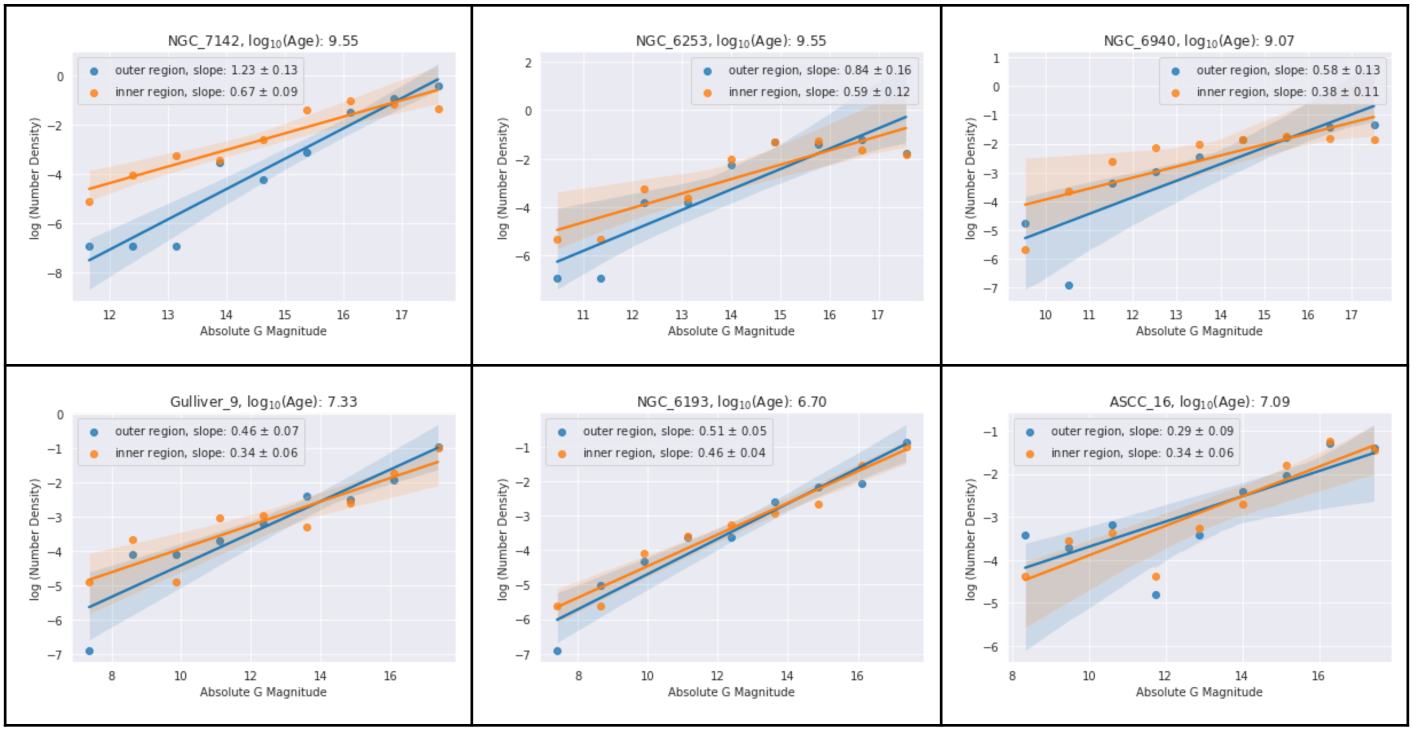

Figure 1: The star number density (in logarithmic scale) for bins of absolute magnitude for both inner and outer regions of three old clusters (top row, log(age) > 8) and young clusters (bottom row, log(age) < 7.5). The blue and orange solid line is the best fit line for the outer and inner region respectively. The shaded regions represent a 95% confidence interval of the regression. The filled circle shows the exact number density for a given magnitude bin. The slope and its standard error are provided in the legend box. Old clusters show a larger separation between the two best fit line even after considering the confidence interval, whereas for two of the young clusters (except Gulliver 9) both lines agree well inside of the confidence interval.

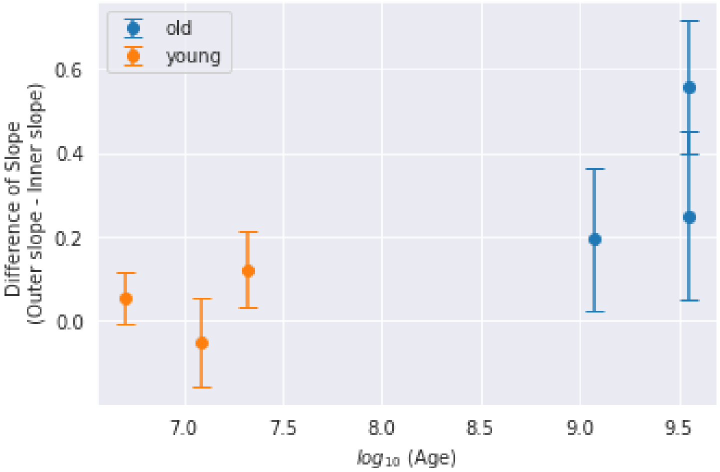

Figure 2: The difference of slope (with their error shown as errorbar) vs the log(age) of the randomly chosen six clusters. Overall the young clusters stay close to 0 with a smaller error, whereas the old clusters show a relatively higher difference in slope with a larger error.

Fig 1 shows that overall the older clusters show a larger difference in slope and they do not align even after considering the 95% confidence interval. A higher number in magnitude means fainter stars, which are usually the low-mass stars in the main sequence line. The outer region's slope is steeper, which suggests that the number of high magnitude stars (thus brighter and high mass stars) decreases in the outer region. But for the younger clusters, there is no noticeable difference in the slope, at least in the random three clusters. This suggests no salient mass segregation in the inner and outer regions for these clusters. Fig 2 strengthens this idea. We can see that the young clusters have smaller differences in slope and we are more confident about that. But for the older cluster, the difference of slope is relatively higher but the error is very high to infer anything strongly.

Overall the figure indicates the idea that the young clusters are relatively less mass segregated, whereas the old clusters are relatively more mass segregated. This is in line with dynamic mass segregation where initially there is not any strong segregation, but over time it gets more segregated. The sample size is very small and the error bar is also quite high. So we cannot strongly support anything, but this surely indicates not primordial mass segregation.

Research Design

Considering the knowledge from the literature and the preliminary analysis, now in this proposal we want to understand whether the mass segregation in open clusters is primordial or dynamic. More specifically we are interested to know how we will measure the mass segregation and how it will vary depending on the mass segregation. If we measure the mass segregation for clusters with varying τ (defined as the ratio of age and relaxation time), then a primordial mass segregation will result in a high segregation for all of the clusters. Because almost all the clusters will be highly segregated irrespective of their τ. Similarly for the same calculation, a dynamic mass segregation will show an increase in mass segregation as τ increases until around $\tau \sim 3.3$ (as Pavlik et al, (2019) suggested this as the time when primordial and dynamic mass segregation aligns). Because for the low τ , the cluster will not be segregated, but as time progresses, due to the two-body interaction, the mass segregation will increase.

The independent variable, τ is calculated from the age and relaxation time. The age will be used from the Dias et al. (2021) dataset. The formula for relaxation time is given as (Allison et al. 2009b):

$$t_{relax} = \frac{N}{8\,ln\,N}\,t_{cross} = \frac{N}{8\,ln\,N}\,\frac{R}{\sigma_v}$$

The total number of members, N and the radius of the clusters, R can be also found in the Dias et al (2021). We have the mean proper motion for the clusters and Cantat-Gaudin et al (2020) provides the list of all members with their proper motion. Using that we will calculate the proper motions of all stars wrt cluster proper motion and its the standard deviation. Once we have proper motion standard deviation, we can multiply by the distance to get the physical velocity dispersion σ_v.

We will use two measurements for the mass segregation (outcome variable). For both methods, first we will fit the observed CMD (color magnitude diagram) with theoretical isochrone (from Girardi et al., 2002) considering distance and extinction data from Dias et al (2021). First we will use the modified version of the MST method (Olczak et al., 2011) with geometric mean as it is more robust to outliers. In MST we need to define, for how many massive stars ($N_{massive}$) we will build the average MST tree. We will check with $N_{massive}$ = 10 as used by Tarricq et al (2022). This can be done with clusters with any number of stars.

Secondly, we will also use the mass function slope difference in the core and outer region of the clusters. The cluster center will be taken from Dias et al. (2021). The cluster member data (distance from cluster center) will be fitted with a theoretical cluster fitting model (Beretta & Hetem, 2018) to find the core radius (radius where the density is 50% of the central density). Then the two regions will be the inside and outside of the core radius. Our quantitative metric will be the difference of slope (outer - inner) between these two regions with error propagated from the standard error of the slope. As we need a large enough number of stars to sample the mass function, this method will only be used with the clusters with more than 200 members.

First, we will do a regression analysis with the MST method outcome $\Lambda_{MSR,\,10}$ vs the τ parameters. We will find the slope and intercept of the regression model to check if there is any significant effect. The effect size will be calculated using the R^2 and the significance will be tested using the p-value of the coefficient of the τ (slope).

Similarly using the output of the mass function, we will make a regression model of mass function slope difference (outer - inner) vs the parameter τ. Again we will find the slope and intercept and their standard error. The significance test will be tested using the p-value of the slope and the effect size by the R^2.

If we can find a significant positive slope in the mass segregation (both by MST and/or mass function) with an intercept close to 0, this will suggest that the mass segregation is increasing over time supporting dynamic mass segregation. On the contrary, if we find a positive intercept and a significant slope around 0, this will indicate that the mass was segregated from the initial time supporting the primordial mass segregation. If we found these results supporting our hypothesis then next we can select individual clusters to do case study and further investigate the mass segregation mechanism.

If we didn't find any significant result, then we can try to run the same regression up until $\tau \sim 3.3$. As this is where both mechanisms should meet (acc to Pavlik et al 2018), we may find a significant increase upto 3.3 τ and then flattening of the curve. We should also visually investigate to see if there are two different population of clusters: one goes from low to high mass segregation from 0 to 3.3 τ, where the second population shows a constant moderate to high segregation over time. This could suggest that some clusters have primordial and others have dynamic mass segregation mechanisms and we could investigate the parameters of these different populations. Another possibility would be to find the clusters who do not show any segregation even after 3.3τ. They are maybe the clusters that do not go through any dynamic evolution. We can remove them from the analysis and run the regression again. Also we can investigate those non-evolving clusters to understand the underlying reasons.

Code Appendix

Cluster Exploration Notebook:

https://colab.research.google.com/drive/1jzFd5pQhymsriWMyYFzUo4YdpgKJbqyS?usp=sharing

HC Appendix

#algorithms: In the code notebook, I want to plot the difference slope plot and find the difference slope and error value for any cluster. Thus I made a wrapper function, where I can just input my member data to get the regression models and the slopes, its error along with the nice plots. I took the entire dataset as input as well as its age so that I can report it nicely in the plots. One problem that I encountered is that sometimes some bins have 0 counts, and taking logs of them gives errors. So I clipped my count by a small minimum value (i.e., 1e-3) to avoid getting NaN while conserving the fact that in that bin the number density is very very low. Also I specified the bin edges based on the maximum and minimum magnitude, so that I can get number estimates for each of the regions in the similar magnitude bins. Otherwise, the bins for inner and outer regions were different, which required us to interpolate the slopes to compare with each other. Along the codes, function name, variable names are chosen effectively for increasing readability.

#dataviz: I generated high quality visualizations to show how the magnitude function slope varies for inner and outer regions for old and young clusters. The legends and captions make the visualizations self-contained. I used separate colors for separate regions and used the same color throughout for better understanding. Similarly the difference of slope vs age plot was plotted as an errorplot to show the size of uncertainty clearly. The old and young clusters are separated by different colors. The axes are labeled properly.

#hypothesisdevelopment: The cause (if the cluster is primordially or dynamically segregated), effect (then the mass segregation will either be higher from the start or gradually increase over time) and mechanism (primordial clusters are already segregated while dynamical cluster will continue towards segregation as τ increases up to 3.3) of the hypothesis are explained. The knowledge from the past papers (for example the idea that $3.3\ \tau$ is when both model would merge) and preliminary data analysis (the difference of slope will be higher for higher age, thus for higher τ) are used to develop the hypothesis. Later it was explained what results will support and what will not support the hypothesis. In both cases, our possible future steps are mentioned.

Bibliography

Allison, R. J., Goodwin, S. P., Parker, R. J., De Grijs, R., Zwart, S. F. P., & Kouwenhoven, M. B. N. (2009a). Dynamical mass segregation on a very short timescale. The Astrophysical Journal, 700(2), L99.

Allison, R. J., Goodwin, S. P., Parker, R. J., Portegies Zwart, S. F., De Grijs, R., & Kouwenhoven, M. B. N. (2009b). Using the minimum spanning tree to trace mass segregation. Monthly Notices of the Royal Astronomical Society, 395(3), 1449-1454.

Berretta, J. L. L., & Hetem Jr, A (2018). Fitting of King's model to young star clusters. Boletim da Sociedade Astronômica Brasileira, 30(1), 126-127.

Cantat-Gaudin, T., & Anders, F. (2020). Clusters and mirages: cataloguing stellar aggregates in the Milky Way. Astronomy & Astrophysics, 633, A99.

Dias, W. S., Monteiro, H., Moitinho, A., Lépine, J. R., Carraro, G., Paunzen, E., ... & Villela, L. (2021). Updated parameters of 1743 open clusters based on Gaia DR2. Monthly Notices of the Royal Astronomical Society, 504(1), 356-371.

Dib, S., & Henning, T. (2019). Star formation activity and the spatial distribution and mass segregation of dense cores in the early phases of star formation. Astronomy & Astrophysics, 629, A135.

Dib, S., Schmeja, S., & Parker, R. J. (2018). Structure and mass segregation in Galactic stellar clusters. Monthly Notices of the Royal Astronomical Society, 473(1), 849-859.

Fragione, G., Pavlík, V., & Banerjee, S. (2018). Neutron stars and millisecond pulsars in star clusters: implications for the diffuse gamma-radiation from the Galactic Centre. Monthly Notices of the Royal Astronomical Society, 480(4), 4955-4962.

Gaia Collaboration, A. G. A. Brown, A. Vallenari, T. Prusti, J. H. J. de Bruijne, C. Babusiaux and C. A. L. Bailer-Jones (2018) Gaia Data Release 2. Summary of the contents and survey properties. ArXiv e-prints. External Links: https://arxiv.org/abs/1804.09365

Hasan, P., & Hasan, S. N. (2011). Mass segregation in diverse environments. Monthly Notices of the Royal Astronomical Society, 413(4), 2345-2357.

Hillenbrand, L. A., & Hartmann, L. W. (1998). A preliminary study of the Orion nebula cluster structure and dynamics. The Astrophysical Journal, 492(2), 540.

Mattern, M., Kainulainen, J., Zhang, M., & Beuther, H. (2018). Structure and fragmentation of a high line-mass filament: Nessie. Astronomy & Astrophysics, 616, A78.

Olczak, C., Spurzem, R., & Henning, T. (2011). A highly efficient measure of mass segregation in star clusters. Astronomy & Astrophysics, 532, A119.

Pavlík, V., Kroupa, P., & Šubr, L. (2019). Do star clusters form in a completely mass-segregated way?. Astronomy & Astrophysics, 626, A79.

Pang, X., Grebel, E. K., Allison, R. J., Goodwin, S. P., Altmann, M., Harbeck, D., ... & Drissen, L. (2013). On the origin of mass segregation in NGC 3603. The Astrophysical Journal, 764(1), 73.

Pang, X., Li, Y., Tang, S. Y., Pasquato, M., & Kouwenhoven, M. B. N. (2020). Different Fates of Young Star Clusters after Gas Expulsion. The Astrophysical Journal Letters, 900(1), L4.

Pang, X., Li, Y., Yu, Z., Tang, S. Y., Dinnbier, F., Kroupa, P., ... & Kouwenhoven, M. B. N. (2021). 3D Morphology of Open Clusters in the Solar Neighborhood with Gaia EDR 3: Its Relation to Cluster Dynamics. The Astrophysical Journal, 912(2), 162.

Plunkett, A. L., Fernández-López, M., Arce, H. G., Busquet, G., Mardones, D., & Dunham, M. M. (2018). Distribution of Serpens South protostars revealed with ALMA. Astronomy & Astrophysics, 615, A9.

Tang, S. Y., Chen, W. P., Chiang, P. S., Jose, J., Herczeg, G. J., & Goldman, B. (2018). Characterization of stellar and substellar members in the Coma Berenices star cluster. The Astrophysical Journal, 862(2), 106.

Tarricq, Y., Soubiran, C., Casamiquela, L., Castro-Ginard, A., Olivares, J., Miret-Roig, N., & Galli, P. A. B. (2022). Structural parameters of 389 local open clusters. Astronomy & Astrophysics, 659, A59.

Zhang, Y., Tang, S. Y., Chen, W. P., Pang, X., & Liu, J. Z. (2020). Diagnosing the Stellar Population and Tidal Structure of the Blanco 1 Star Cluster. The Astrophysical Journal, 889(2), 99.

Zonoozi, A. H., Haghi, H., Kroupa, P., Küpper, A. H., & Baumgardt, H. (2017). Direct N-body simulations of globular clusters–III. Palomar 4 on an eccentric orbit. Monthly Notices of the Royal Astronomical Society, 467(1), 758-767.