

Primordial mass segregation of star clusters: The role of binary stars

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Abstract. Observational results of young star-forming regions suggest that star clusters are completely mass segregated at birth. As a star cluster evolves dynamically, these initial conditions are gradually lost. For star clusters with single stars only and a canonical IMF, it has been suggested that traces of these initial conditions vanish at τ_v between 3 and 3.5 half-mass relaxation times. Here, by means of numerical models, we investigate the role of the primordial binary population on the loss of primordial mass segregation. We found that τ_v does not depend on the binary star distribution, yielding $3 < \tau_v/t_{\text{rh}} < 3.5$. We also conclude that the completely mass segregated clusters, even with binaries, are more compatible with the present-day ONC than the non-segregated ones.

Key words: methods: numerical, data analysis – star clusters: individual (ONC) – stars: formation, binaries

1. Introduction

Mass segregation is a prominent feature present in evolved star clusters due to their dynamical evolution (e.g. Chandrasekhar, 1943; Chandrasekhar & von Neumann, 1942, 1943) but not only there. Recent *ALMA* observations of the Serpens South star-forming region by Plunkett et al. (2018) suggest that young clusters are born completely mass segregated. Despite observing a general tendency of clusters to evolve towards higher mass segregation, it may both increase and decrease due to two-body encounters that lead to energy equipartition. In (Pavlík et al., 2019a, hereafter Paper I), we were the first to point out that the degree of mass segregation of a non-segregated and a completely segregated system is gradually settled at a similar level, their primordial differences vanish and both initial conditions become observationally indistinguishable after some time designated as τ_v . Based on our numerical N -body models with single stars, we estimated this time to $3 < \tau_v/t_{\text{rh}} < 3.5$ (where t_{rh} is the half-mass

relaxation time; cf. Spitzer & Hart, 1971). Most (if not all) stars are preferentially born in binary systems (e.g. Kroupa, 1995; Goodwin & Kroupa, 2005) – 42 % of field (i.e. old) M-dwarfs (Fischer & Marcy, 1992), 45 % of K-dwarfs (Mayor et al., 1992) or 57 % of G-dwarfs (Duquennoy & Mayor, 1991; Raghavan et al., 2010) are reported in binaries, and the binary fraction increases with the stellar mass. Hence, for this conference contribution, we extend the work of Paper I by studying the evolution of mass segregation in star clusters that include primordial binaries.

2. Models

We evolved several realisations of N -body models with 2.4k stars (comparable number to the Orion Nebula Cluster, ONC, Pavlík et al., 2019b) and with the Kroupa (2001) IMF for several relaxation times using `nbody6` (Aarseth, 2003). For each model, we used two extreme primordial mass segregations according to a method of Baumgardt et al. (2008) – none or complete.

In all models, we injected a conservative 50% binary fraction initially (i.e. 601 binary stars in total), while the binary pairing was drawn from a uniform distribution of mass ratio ($0.1 < q < 1.0$) in the mass range above $5 M_{\odot}$ and was random for the remaining stars up to the desired percentage (cf. Küpper et al., 2011) – the model is labelled `P:uni`. The semi-major axes were distributed according to Sana et al. (2012) and Oh et al. (2015) period distributions for stars with $m > 5 M_{\odot}$ and according to Kroupa (1995) for lower-mass stars. Eccentricity distribution of high-mass systems is taken from Sana & Evans (2011) and is thermal for low-mass stars (cf. Heggie, 1975; Duquennoy & Mayor, 1991; Kroupa, 2008).

3. Results

Our clusters with binaries evolve in a similar fashion to the single star models presented in Paper I (compare the plots in Fig. 1). The primordially fully mass segregated clusters lose their initial ordering gradually before settling at some level of mass segregation. Clusters without initial mass segregation establish it dynamically and *again* settle almost at the same level. As in Paper I, we investigate the evolution of mass segregation using the spatial distribution of mean mass and the integral parameter A , i.e. for a k -th bin at radius r_k

$$A = \sum_{k=1}^{n_{\text{bin}}} \frac{\langle m(r_k) \rangle}{\Delta r_k}, \quad \text{with } \langle m(r_k) \rangle = \frac{\sum_{i=1}^k m_i}{\sum_{i=1}^k n_i}, \quad (1)$$

where n_i and m_i are the number of stars and their total mass in an i -th bin, respectively, Δr_k is the width of the k -th bin and n_{bin} is the total number of bins (bins here are logarithmically equidistant). In particular, $r_1 = 0.1$ pc, $r_{n_{\text{bin}}} = 10$ pc and $n_{\text{bin}} = 50$.

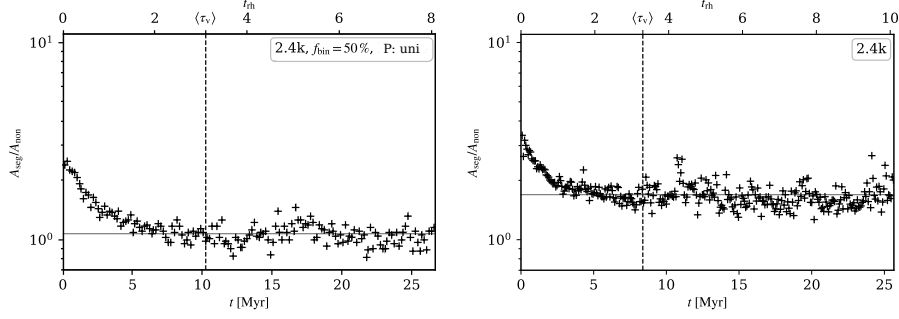


Figure 1. Evolution of the ratio given by Eq. (1) in time. The dashed line and the value $\langle \tau_v \rangle$ represent the mean time when the slope of the data points became flat. The corresponding horizontal slope is plotted by a grey line. The left plot presents a model with initial binary population, the right plot is taken from Paper I for comparison.

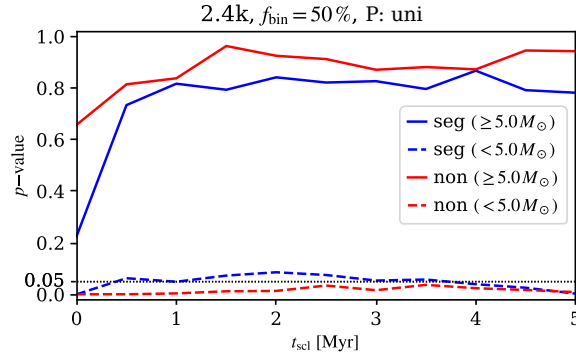


Figure 2. Results of the KS test between the ONC data and our model with 50% binaries. Only the model with scaling and extinction is shown.

The time when the difference of initial conditions vanishes seems independent on the initial binary star fraction. Systems with 50% binaries (P:uni) have $3 < \tau_v/t_{rh} < 3.5$ (see the left panel of Fig. 1) which is equivalent to the systems of similar population with single stars only from Paper I (see the right panel of Fig. 1).

We also tested whether the initial conditions with binaries are still compatible with the observed ONC. In the case of the primordially mass-segregated models, those where elongation (scaling) of the cluster and extinction was accounted for (cf. Sect. 4 in Paper I) have the KS test $p > 0.05$ at the time which is equivalent to the current age of the ONC, i.e. 2.5 Myr (see Fig. 2). In the case

of the initially non-segregated models, none is compatible with the present-day ONC, not even with scaling and extinction.

4. Conclusions

This conference contribution is a follow-up of the work of Pavlík et al. (2019a, Paper I). We have started to investigate the role of a primordial binary star population on mass segregation in star clusters of the size of the ONC.

In the models with 50% initial binary stars, the mean time when the primordially mass segregated and the non-segregated models became indistinguishable was $\langle \tau_v \rangle \approx 3.2 t_{\text{rh}}$, i.e. comparable to the single star models presented in Paper I.

We have also compared our models with the present-day Orion Nebula Cluster. The only compatible model is the one with primordial mass segregation if we also account for interstellar extinction and scaling of the ONC, as presented in Paper I.

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References

- Aarseth, S. J. 2003, *Gravitational N-Body Simulations* (Cambridge, UK: Cambridge University Press)
- Baumgardt, H., De Marchi, G., & Kroupa, P., Evidence for Primordial Mass Segregation in Globular Clusters. 2008, *Astrophys. J.*, **685**, 247, DOI: 10.1086/590488
- Chandrasekhar, S., Dynamical Friction. I. General Considerations: the Coefficient of Dynamical Friction. 1943, *Astrophys. J.*, **97**, 255, DOI: 10.1086/144517
- Chandrasekhar, S. & von Neumann, J., The Statistics of the Gravitational Field Arising from a Random Distribution of Stars. I. The Speed of Fluctuations. 1942, *Astrophys. J.*, **95**, 489, DOI: 10.1086/144420
- Chandrasekhar, S. & von Neumann, J., The Statistics of the Gravitational Field Arising from a Random Distribution of Stars II. 1943, *Astrophys. J.*, **97**, 1, DOI: 10.1086/144487
- Duquennoy, A. & Mayor, M., Multiplicity among solar-type stars in the solar neighbourhood. II - Distribution of the orbital elements in an unbiased sample. 1991, *Astron. Astrophys.*, **500**, 337
- Fischer, D. A. & Marcy, G. W., Multiplicity among M Dwarfs. 1992, *Astrophys. J.*, **396**, 178, DOI: 10.1086/171708

- Goodwin, S. P. & Kroupa, P., Limits on the primordial stellar multiplicity. 2005, *Astron. Astrophys.*, **439**, 565, DOI: 10.1051/0004-6361:20052654
- Heggie, D. C., Binary evolution in stellar dynamics. 1975, *Mon. Not. R. Astron. Soc.*, **173**, 729, DOI: 10.1093/mnras/173.3.729
- Kroupa, P., Inverse dynamical population synthesis and star formation. 1995, *Mon. Not. R. Astron. Soc.*, **277**, 1491, DOI: 10.1093/mnras/277.4.1491
- Kroupa, P., On the variation of the initial mass function. 2001, *Mon. Not. R. Astron. Soc.*, **322**, 231, DOI: 10.1046/j.1365-8711.2001.04022.x
- Kroupa, P. *Initial Conditions for Star Clusters*, ed. S. J. Aarseth, C. A. Tout, & R. A. Mardling, , Vol. **760**, 181
- Küpper, A. H. W., Maschberger, T., Kroupa, P., & Baumgardt, H., Mass segregation and fractal substructure in young massive clusters I. The McLuster code and method calibration. 2011, *Monthly Notices of the Royal Astronomical Society*, **417**, 2300, DOI: 10.1111/j.1365-2966.2011.19412.x
- Mayor, M., Duquennoy, A., Halbwachs, J. L., & Mermilliod, J. C., CORAVEL Surveys to Study Binaries of Different Masses and Ages. 1992, in *Astronomical Society of the Pacific Conference Series*, Vol. **32**, *IAU Colloq. 135: Complementary Approaches to Double and Multiple Star Research*, ed. H. A. McAlister & W. I. Hartkopf, 73
- Oh, S., Kroupa, P., & Pflamm-Altenburg, J., Dependency of Dynamical Ejections of O Stars on the Masses of Very Young Star Clusters. 2015, *Astrophys. J.*, **805**, 92, DOI: 10.1088/0004-637X/805/2/92
- Pavlík, V., Kroupa, P., & Šubr, L., Do star clusters form in a completely mass-segregated way? 2019a, *arXiv e-prints*, arXiv:1905.09289
- Pavlík, V., Kroupa, P., & Šubr, L., VizieR Online Data Catalog: ONC stars masses from literature (Pavlik+, 2019). 2019b, *VizieR Online Data Catalog*, J/A+A/626/A79
- Plunkett, A. L., Fernández-López, M., Arce, H. G., et al., Distribution of Serpens South protostars revealed with ALMA. 2018, *ArXiv e-prints*
- Raghavan, D., McAlister, H. A., Henry, T. J., et al., A Survey of Stellar Families: Multiplicity of Solar-type Stars. 2010, *The Astrophysical Journal Supplement Series*, **190**, 1, DOI: 10.1088/0067-0049/190/1/1
- Sana, H., de Mink, S. E., de Koter, A., et al., Binary Interaction Dominates the Evolution of Massive Stars. 2012, *Science*, **337**, 444, DOI: 10.1126/science.1223344
- Sana, H. & Evans, C. J., The multiplicity of massive stars. 2011, in *IAU Symposium*, Vol. **272**, *Active OB Stars: Structure, Evolution, Mass Loss, and Critical Limits*, ed. C. Neiner, G. Wade, G. Meynet, & G. Peters, 474–485
- Spitzer, Jr., L. & Hart, M. H., Random Gravitational Encounters and the Evolution of Spherical Systems. I. Method. 1971, *Astrophys. J.*, **164**, 399, DOI: 10.1086/150855