Compact Objects and Binaries in Dense Star Clusters
Proceedings IAU Symposium No. 398, 2026
H. M. Lee, J. Hong & R. Spurzem, eds.
doi:10.1017/S1743921325104821

Dynamic Relationship Between Star Cluster Evolution and Tidal Stream Formation

Long Wang[1,2], Tereza Jerabkova[3], Mark Gieles[4,5,6], Holger Baumgardt[7], Chengyuan Li[1,2], Xiaoying Pang[8] and Baitian Tang[1,2]

[1]School of Physics and Astronomy, Sun Yat-sen University, Daxue Road, Zhuhai, 519082, China
email: longwang.astro@live.com

[2]CSST Science Center for the Guangdong-Hong Kong-Macau Greater Bay Area, Zhuhai, 519082, China

[3]Department of Theoretical Physics and Astrophysics, Faculty of Science, Masaryk University, Kotlářská 2, Brno 611 37, Czech Republic

[4]ICREA, Pg. Lluís Companys 23, E08010 Barcelona, Spain

[5]Institut de Ciències del Cosmos (ICCUB), Universitat de Barcelona (UB), c. Martí i Franquès 1, 08028 Barcelona, Spain

[6] Institut d'Estudis Espacials de Catalunya (IEEC), Edifici RDIT, Campus UPC, 08860 Castelldefels

[7]School of Mathematics and Physics, The University of Queensland, St. Lucia, QLD 4072, Australia

[8]Department of Physics, Xi'an Jiaotong-Liverpool University, 111 Ren'ai Road, Suzhou Dushu Lake Science and Education Innovation District, Suzhou Industrial Park, Suzhou 215123, P.R. China

Abstract. Tidal streams from star clusters preserve their dynamical histories and the imprint of the galactic environment. Using the PETAR code, we model cluster evolution with single and binary stellar evolution in a time-dependent Galactic tidal field. Applied to the Hyades open cluster and the Palomar 5 globular cluster, our N-body models show that massive stars and black holes (BHs) accelerate cluster evolution. In Hyades-like open clusters, survival time depends sensitively on the number of OB stars. In Palomar 5, the extended radius can be explained by a large BH population, requiring observational confirmation from binary observations, such as detecting BH-binary systems. Because the escape rate of stars depends on the BH population, stream properties can therefore indicate host-cluster formation conditions and constrain the initial mass function, BH content, and primordial binaries, motivating further study.

Keywords. (Galaxy:) open clusters and associations: individual (Hyades), (Galaxy:) globular clusters: individual (Palomar 5), methods: n-body simulations

1. Introduction

The Gaia survey provides rich kinematic data on stars, ushering in a new era in stellar dynamics. Using these data, numerous stellar streams have been identified across various systems, including young star-forming regions (Kounkel and Covey 2019; Jerabkova et al. 2019; Beccari et al. 2020; Meingast et al. 2019), open clusters (Jerabkova et al. 2021; Meingast et al. 2021; Kos 2024; Risbud et al. 2025), and globular clusters (GCs)

© The Author(s), 2026. Published by Cambridge University Press on behalf of The International Astronomical Union.

https://doi.org/10.1017/S1743921325104821 Published online by Cambridge University Press

(Ibata et al. 2024; Bonaca and Price-Whelan 2025). These streams offer new opportunities to investigate the dynamical evolution of their progenitor stellar systems.

Among these systems, star clusters are gravitationally bound groups whose members form in the same environment, making them ideal laboratories for studying star formation and evolution. However, as collisional systems, their global properties, such as density profiles, stellar mass functions, and binary characteristics, are substantially altered by dynamical processes including two-body relaxation, mass segregation, binary formation and evolution, and tidal evaporation. Consequently, present-day observations do not reflect their initial states. This is especially true after significant stellar escape or the evolution of massive stars into dark remnants, which makes it challenging to infer the initial conditions of the clusters.

In contrast, stellar streams originating from star clusters are so diffuse that collisional effects are negligible. Their global properties (e.g., mass function, binary properties) therefore remain unchanged and reflect the state at the time stars escape into the stream. This suggests that different regions of a stream preserve stellar properties from different stages of dynamical evolution, helping to constrain the initial conditions of star clusters.

Achieving this requires self-consistent models of both clusters and their streams. Although such studies are still limited, advances in numerical tools and computational resources now make it feasible to build these models for open clusters and GCs (e.g. Küpper et al. 2008; Renaud et al. 2011; Dinnbier and Kroupa 2020; Wan et al. 2021, 2023; Jerabkova et al. 2021; Gieles et al. 2021; Webb and Bovy 2020, 2022; Boffin et al. 2022; Wang and Jerabkova 2021; Wang et al. 2024; Thomas et al. 2023; Arnold and Baumgardt 2025).

The PETAR code (Wang *et al.* 2020a) is an N-body code designed for star-by-star simulations of star clusters including their streams. It integrates the parallel particle framework FDPS (Iwasawa et al. 2016, 2020), the accurate binary-interaction module SDAR (Wang et al. 2020b) based on slowdown algorithmic regularization, updated single and binary stellar evolution (SSE, BSE) (Hurley et al. 2000; Hurley et al. 2002; Banerjee et al. 2020), as well as MOBSE (Giacobbo et al. 2018), BSEEMP (Tanikawa *et al.* 2020), and the galactic tidal field package GALPY (Bovy 2015). Ongoing updates to PETAR include the implementation of the stellar and binary evolution code SEVN (Iorio *et al.* 2023) and the galactic potential library AGAMA (Vasiliev 2019). Using PETAR, Wang and Jerabkova (2021) and Wang et al. (2024) built star-by-star models of the Hyades open cluster and the globular cluster Palomar 5. Here, we summarize those results and examine how the initial mass function (IMF), black holes (BHs), and binaries shape the evolution of Hyades and Palomar 5.

2. Influence of randomly sampling IMF on survival of open clusters

Using the convergent point (CP) method with Gaia data, Jerabkova et al. (2021) discovered 800 pc-long tidal tails around the Hyades, demonstrating that the CP method efficiently detects extended tails independent of the assumed Galactic potential. In follow-up work, Wang and Jerabkova (2021) used N-body simulations to constrain the Hyades' initial conditions and showed that the underlying IMF physics–whether star formation is purely stochastic or self-regulated–critically affects the tidal disruption and survival of low-mass, Hyades-like clusters. As illustrated in Figure 1, randomly sampling the Kroupa (2001) IMF to a total mass of about 800 $M_\odot$ over 300 realizations yields large variations in the number of OB stars ($> 5\,M_\odot$), even though the mean matches the IMF expectation. Consequently, both the maximum stellar mass $m_{\rm max}$ and the total OB-star mass $M_{\rm OB}$ vary substantially (Figure 2).

Wang and Jerabkova (2021) simulated Hyades-like clusters with PETAR for each IMF realization up to 648 Myr, adopting identical initial conditions: a Plummer density profile,

https://doi.org/10.1017/S1743921325104821 Published online by Cambridge University Press

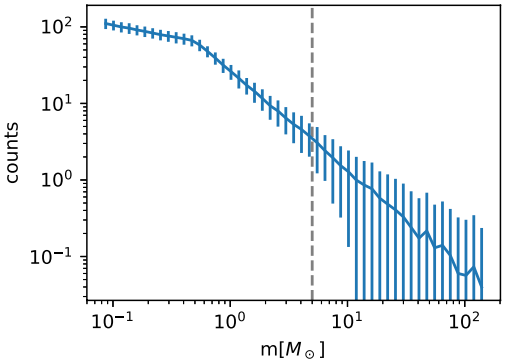


Figure 1. Mean and standard deviation of star counts from 300 random samples of the Kroupa (2001) IMF with total mass $M \approx 800\,M_\odot$.

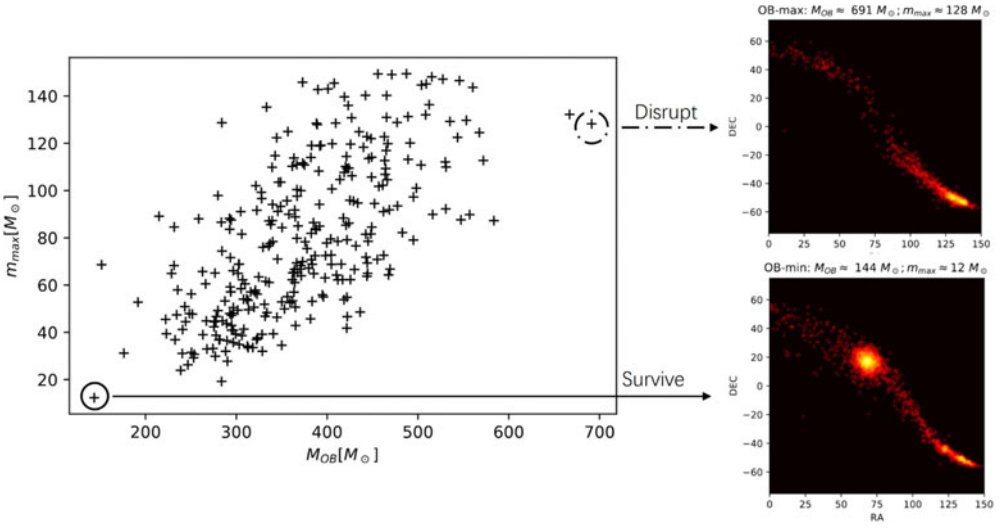


Figure 2. Left: Maximum mass $m_{\rm max}$ versus total OB-star mass ($> 5\,M_\odot$) $M_{\rm OB}$ from IMF sampling of Figure 1. Right: RA-Dec contour maps of star clusters and tidal streams from two simulations with the same initial $r_{\rm h} = 2$ pc and $M = 800\,M_\odot$, showing the cases with maximum and minimum $M_{\rm OB}$, respectively. Figures adapted from Wang and Jerabkova (2021).

half-mass radius $r_{\rm h} = 2$ pc, virial equilibrium, no primordial binaries, and the Galactic potential using MWPotential2014 (Bovy 2015). The outcomes differ markedly with $m_{\rm max}$ and $M_{\rm OB}$: the largest $M_{\rm OB}$ leads to complete disruption leaving only streams, whereas the smallest $M_{\rm OB}$ yields a surviving open cluster akin to the Hyades.

We identify two mechanisms that drive the large differences in cluster evolution. First, stellar-wind mass loss from OB stars–most pronounced in the first 30 Myr–removes substantial mass (Figure 3). OB stars shed mass and evolve into neutron stars or BHs, while low-mass stars lose comparatively little. A larger $M_{\rm OB}$, therefore, induces a greater cluster mass loss, rapidly reducing the tidal radius $r_{\rm tid}$ and total mass $M_{\rm tid}$. The cluster then experiences stronger tidal disruption and cannot survive to 600 Myr.

Second, BHs formed from massive OB stars alter the long-term dynamics. Figure 4 compares five simulations with similar $M_{\rm tid}$ and $r_{\rm h}$ at 30 Myr, minimizing the effect of early wind mass loss, yet their subsequent evolution diverges. The surviving model does

https://doi.org/10.1017/S1743921325104821 Published online by Cambridge University Press

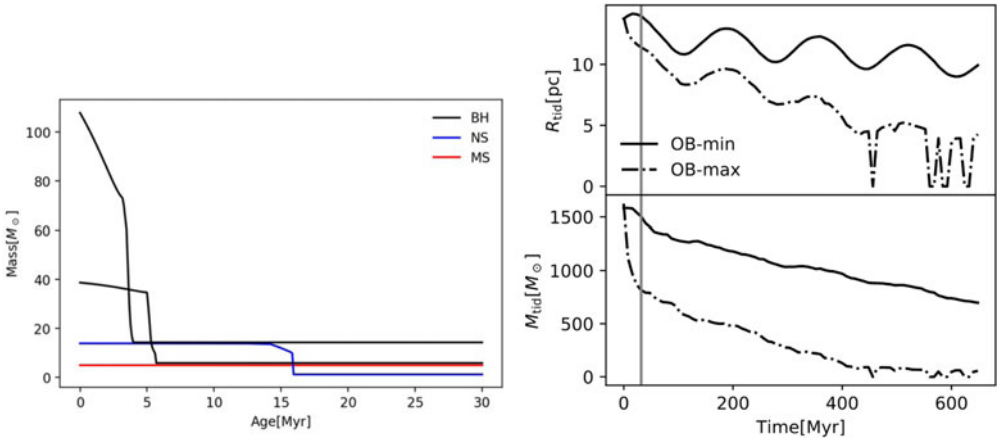


Figure 3. Left: Mass evolution during the first 30 Myr for different types of solar-metallicity stars using SSE code. Right: Evolution of the tidal radius $r_{\rm tid}$ and total mass $M_{\rm tid}$ for the simulations in Figure 2, adapted from Figure 5 of Wang and Jerabkova (2021).

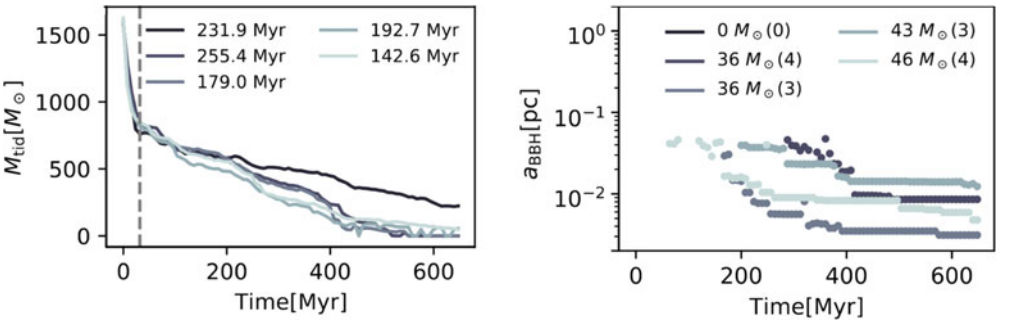


Figure 4. Left: Mass evolution for five models with similar $r_{\rm h}$ and $M_{\rm tid}$ at 30 Myr. Right: corresponding evolution of binary BH semi-major axes $a_{\rm BBH}$. Figures adapted from Figure 7 of Wang and Jerabkova (2021).

not contain BHs, whereas the others retain 3–4 BHs. These BHs form binary black holes (BBHs) that act as energetic heating sources: as their semi-major axes $a_{\rm BBH}$ shrink, repeated interactions eject surrounding stars. The resulting lower-density clusters are more vulnerable to tidal forces and disrupt earlier.

The findings of Wang and Jerabkova (2021) show that massive OB stars strongly influence the long-term evolution of low-mass clusters like the Hyades, complicating efforts to constrain their initial conditions. However, tidal streams preserve the history of tidal disruption and provide additional data, such as star counts, that could potentially enable better constraints (Figure 8 in Wang and Jerabkova 2021), worth further study.

3. Influence of black holes and primordial binary on globular cluster Palomar 5

Palomar 5 is notable for its extended tidal tails, indicating strong tidal mass loss. It also has unusually low density and an extended core compared to other GCs. Using N-body simulations, Gieles et al. (2021) showed that reproducing the observed density profile requires either a large BH population that heats the core or an initially looser cluster; current observations cannot distinguish these scenarios. Wang et al. (2024) extended

https://doi.org/10.1017/S1743921325104821 Published online by Cambridge University Press

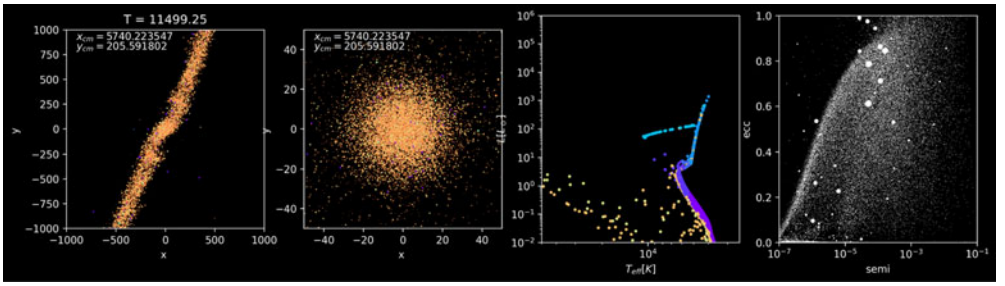


Figure 5. Snapshot of projected positions in the x–y (galactic disk) plane, HR diagram, and binary semi-major axis-eccentricity distributions for Palomar 5 simulations with BHs and primordial binaries at ≈ 11.5 Gyr. Data from Wang et al. (2024).

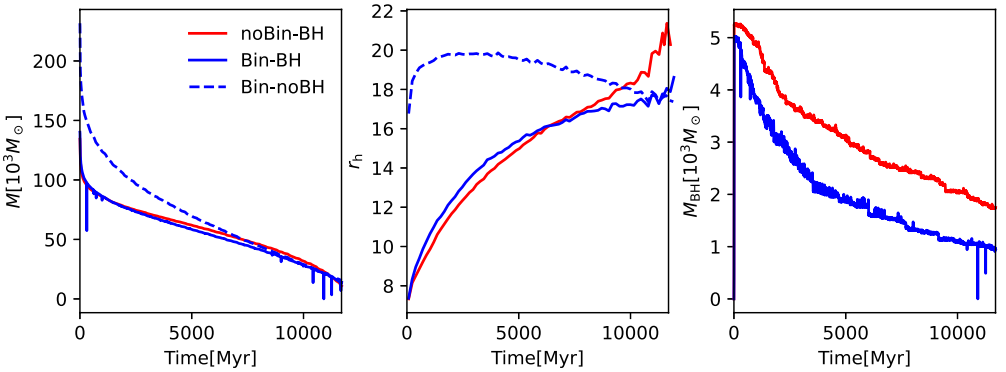


Figure 6. Evolution of M, r_h, and total BH mass M_{BH} across three Palomar models, comparing binaries vs. no binaries (Bin/noBin) and BHs vs. no BHs (BH/noBH). Data is from Wang et al. (2024).

this with N-body simulations with and without BHs and primordial binaries, examining observable binary features and mass functions. Figure 5 presents a Bin-BH model at Palomar 5's age, showing the tidal stream, resolved stellar populations and binary properties.

Compared with the presence of BHs, the existence of primordial binaries has a much weaker impact on cluster structural evolution (Figure 6). To reach the same final M and r_h, BH-free models (Bin-noBH) require much larger initial mass and r_h than BH models (Bin-BH and noBin-BH). Among BH models, the M and r_h evolutions are similar with or without binaries, except that the total BH mass M_{BH} is lower when binaries are present because early OB-binary mergers reduce BH progenitors.

Different evolutionary histories in models with and without BHs lead to a distinct binary evolution. In the denser, BH-heated systems, the hard-soft boundary is smaller, increasing binary disruption and altering the period distribution. Figure 7 shows the number-density map of binary binding energy E_b versus cluster-centric distance r. Binaries within 100 pc lie inside the cluster; those beyond are in the tidal streams.

The two models show no clear difference in the E_b distribution, although the Bin-BH case has a lower binary fraction and includes several binaries containing BH. Binaries with BH and main sequence stars (BH-MS) could be identified via multi-epoch radial-velocity measurements, providing potential evidence for BHs in Palomar 5.

A large fraction of binaries have escaped through the tidal stream, exhibiting a wider E_b distribution than cluster-bound binaries. As shown by Wang et al. (2024), the distant

https://doi.org/10.1017/S1743921325104821 Published online by Cambridge University Press

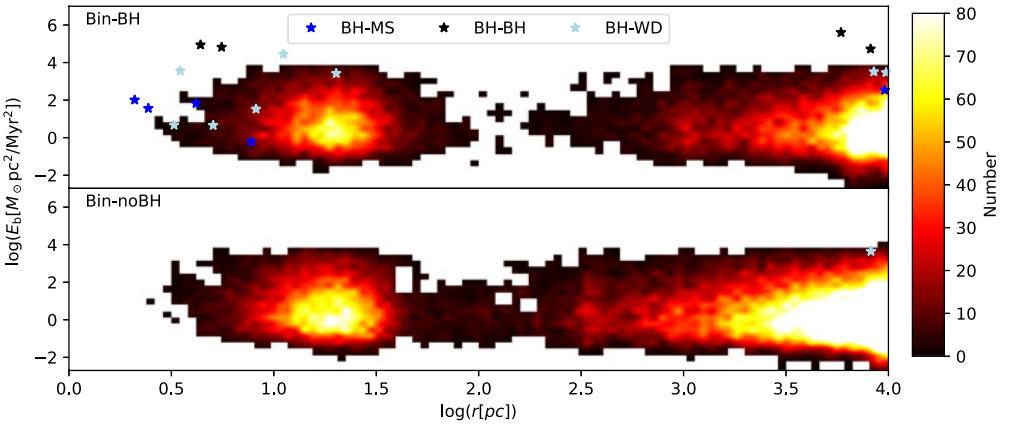


Figure 7. Number-density map of binary binding energy versus cluster-centric distance for Palomar 5 simulations, comparing models with primordial binaries with and without BHs. In BH models, BH-MS, BH-BH, and BH-WD binaries are marked with stars. Figure adapted from Figure 8 in Wang et al. (2024).

tidal tails should host a higher binary fraction because escaped binaries experience fewer encounters, allowing wide systems to survive—unlike the inside of clusters. This trend can help link halo and GC binary populations and constrain the initial wide-binary properties in GCs.

4. Conclusion

Studies of the Hyades and Palomar 5 show that massive stars with high mass loss–the progenitors of BHs–can strongly shape the long-term evolution of both low-mass open clusters and globular clusters. This influence complicates inferring initial cluster conditions from present-day observations. Tidal streams, which record stars' escape histories, offer additional constraints. Future work should explore the dynamical relationship between the cluster and the stream, including the roles of gas expulsion and rotation in stream formation and evolution (e.g., Dinnbier and Kroupa 2020), and how time-dependent Galactic potentials (bar, spiral arms) interact with the dynamics of the internal cluster to shape streams.

References

Arnold, A. D. & Baumgardt, H. 2025, *MNRAS*, 537(2), 1807–1817.
Banerjee, S., Belczynski, K., Fryer, C. L., Berczik, P., Hurley, J. R., Spurzem, R., & Wang, L. 2020, *A&A*, 639, A41.
Beccari, G., Boffin, H. M. J., & Jerabkova, T. 2020, *MNRAS*, 491(2), 2205–2216.
Boffin, H. M. J., Jerabkova, T., Beccari, G., & Wang, L. 2022, *MNRAS*, 514(3), 3579–3592.
Bonaca, A. & Price-Whelan, A. M. 2025, *New Astron. Revs*, 100, 101713.
Bovy, J. 2015, *ApJS*, 216(2), 29.
Dinnbier, F. & Kroupa, P. 2020, *A&A*, 640, A85.
Giacobbo, N., Mapelli, M., & Spera, M. 2018, *MNRAS*, 474(3), 2959–2974.
Gieles, M., Erkal, D., Antonini, F., Balbinot, E., & Peñarrubia, J. 2021, *Nature Astron*, 5, 957–966.
Hurley, J. R., Pols, O. R., & Tout, C. A. 2000, *MNRAS*, 315(3), 543–569.
Hurley, J. R., Tout, C. A., & Pols, O. R. 2002, *MNRAS*, 329(4), 897–928.
Ibata, R., Malhan, K., Tenachi, W., Ardern-Arentsen, A., Bellazzini, M., Bianchini, P., Bonifacio, P., Caffau, E., Diakogiannis, F., Errani, R., Famaey, B., Ferrone, S., Martin, N. F., di Matteo, P., Monari, G., Renaud, F., Starkenburg, E., Thomas, G., Viswanathan, A., & Yuan, Z. 2024, *ApJ*, 967(2), 89.

https://doi.org/10.1017/S1743921325104821 Published online by Cambridge University Press

Iorio, G., Mapelli, M., Costa, G., Spera, M., Escobar, G. J., Sgalletta, C., Trani, A. A., Korb, E., Santoliquido, F., Dall'Amico, M., Gaspari, N., & Bressan, A. 2023, *MNRAS*, 524(1), 426–470.
Iwasawa, M., Namekata, D., Nitadori, K., Nomura, K., Wang, L., Tsubouchi, M., & Makino, J. 2020, *PASJ*, 72(1), 13.
Iwasawa, M., Tanikawa, A., Hosono, N., Nitadori, K., Muranushi, T., & Makino, J. 2016, *PASJ*, 68(4), 54.
Jerabkova, T., Boffin, H. M. J., Beccari, G., & Anderson, R. I. 2019, *MNRAS*, 489(3), 4418–4428.
Jerabkova, T., Boffin, H. M. J., Beccari, G., de Marchi, G., de Bruijne, J. H. J., & Prusti, T. 2021, *A&A*, 647, A137.
Kos, J. 2024, *A&A*, 691, A28.
Kounkel, M. & Covey, K. 2019, Untangling the Galaxy. I. Local Structure and Star Formation History of the Milky Way. *AJ*, 158(3), 122.
Kroupa, P. 2001, *MNRAS*, 322(2), 231–246.
Küpper, A. H. W., MacLeod, A., & Heggie, D. C. 2008, *MNRAS*, 387(3), 1248–1252.
Meingast, S., Alves, J., & Fürnkranz, V. 2019, *A&A*, 622, L13.
Meingast, S., Alves, J., & Rottensteiner, A. 2021, *A&A*, 645, A84.
Renaud, F., Gieles, M., & Boily, C. M. 2011, *MNRAS*, 418(2), 759–769.
Risbud, D., Jadhav, V. V., & Kroupa, P. 2025, *A&A*, 694, A258.
Tanikawa, A., Yoshida, T., Kinugawa, T., Takahashi, K., & Umeda, H. 2020, *MNRAS*, 495(4), 4170–4191.
Thomas, G. F., Famaey, B., Monari, G., Laporte, C. F. P., Ibata, R., de Laverny, P., Hill, V., & Boily, C. 2023, *A&A*, 678, A180.
Vasiliev, E. 2019, *MNRAS*, 482(2), 1525–1544.
Wan, Z., Arnold, A. D., Oliver, W. H., Lewis, G. F., Baumgardt, H., Gieles, M., Hénault-Brunet, V., de Boer, T., Balbinot, E., Da Costa, G., Mackey, D., Erkal, D., Ferguson, A., Kuzma, P., Pancino, E., Peñarrubia, J., Sanna, N., Sollima, A., van der Marel, R. P., & Watkins, L. L. 2023, *MNRAS*, 519(1), 192–207.
Wan, Z., Oliver, W. H., Baumgardt, H., Lewis, G. F., Gieles, M., Hénault-Brunet, V., de Boer, T., Balbinot, E., Da Costa, G., & Mackey, D. 2021, *MNRAS*, 502(3), 4513–4525.
Wang, L., Gieles, M., Baumgardt, H., Li, C., Pang, X., & Tang, B. 2024, *MNRAS*, 527(3), 7495–7514.
Wang, L., Iwasawa, M., Nitadori, K., & Makino, J. 2020a, *MNRAS*, 497a(1), 536–555.
Wang, L. & Jerabkova, T. 2021, *A&A*, 655, A71.
Wang, L., Nitadori, K., & Makino, J. 2020b, *MNRAS*, 493b(3), 3398–3411.
Webb, J. J. & Bovy, J. 2020, *MNRAS*, 499(1), 116–128.
Webb, J. J. & Bovy, J. 2022, *MNRAS*, 510(1), 774–785.

https://doi.org/10.1017/S1743921325104821 Published online by Cambridge University Press