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# The effect of the Galactic tidal field onto the distribution of stars in the Milky Way globular clusters

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## ABSTRACT

**Key words:** methods: numerical – galaxies: formation – galaxies: star clusters: general.

## 1 INTRODUCTION

We investigate whether the distribution of stars in the MW GCs is consistent with their orbits in the Galactic potential.

Effect of tidal shocks on clusters

- Webb et al. (2018)
- (Aguilar & White 1985, 1986)
- Spitzer (1958)
- Spitzer (1987)
- Gieles et al. (2006)
- Kruijssen et al. (2011)
- Gieles & Renaud (2016)

"By defining a tidal heating parameter (Gnedin 2003), cluster's mass loss history can be estimated for any known tidal history." `https://arxiv.org/pdf/1911.01548.pdf` "If the dynamical evolution timescale is larger than the orbital period, these stripped stars remain for some time on approximately the mean orbit of the progenitor (Lynden-Bell & Lynden-Bell 1995)"

We summarise observations of the distribution of stars in the MW GCs and the initial conditions for the orbit integrations in section 2. We present our method in section 3, results in section 4, discussion in section 5 and conclude in section **??**.

## 2 OBSERVATIONS

Recent observational catalogues now provide full 6D phase space information for the Milky Way (MW) globular cluster (GC) system. Baumgardt et al. (2019); Hilker et al. (2020) published[1] mean proper motions (PMs) and line-of-sight (radial) velocities (RVs) of 159 MW GCs and compiled velocity dispersion profiles of 141 MW GCs. The authors combined PMs from HST (Bellini et al. 2014; Watkins et al. 2015) and *Gaia* DR2 measurements with RVs from MUSE integral-field spectroscopy (Kamann et al. 2018) and from the WAGGS survey and archival AAT data (Dalgleish et al. 2020).

The details of the N-body models can be found in Baumgardt (2017), and Baumgardt & Hilker (2018). Details on the stellar mass functions can be found in Sollima & Baumgardt (2017). Finally, the rotation profiles of the clusters were derived in Sollima et al. (2019).

In addition, de Boer et al. (2019) studied the distribution of stars in 81 MW GCs using observations of their radial number density profiles stitched together from *Gaia* DR2 (Gaia Collaboration et al. 2016a,b; Lindegren et al. 2018) observations of the outer regions together with 26 Hubble Space Telescope (HST) star count profiles (Miocchi et al. 2013) plus ground-based surface brightness profiles (Trager et al. 1995a,b) of the inner regions.

Decide which references suffice for DR2, so either drop or include the following: "parallax and PM down to G=21 (Evans+ 2018, Lindegren+ 2018, Riello+ 2018), RVs from *Gaia* RV spectrometer (RVS) spectrograph (Cropper+ 2018, Sartoretti+ 2018), dust maps (Schlegel+ 1998) /w coefficients from Schlafly & Finkbeiner 2011, extinction from Schlegel+ 1998, Harris+ 1996, 2010 ed"

The authors fit the lowered isothermal models of King (1966), Wilson (1975), Gieles & Zocchi (2015, 2018) and the spherical models of star clusters with potential escapers (SPES, Claydon et al. 2017, 2019) using the LIMEPY code (Gieles & Zocchi 2015, 2018).

Paraphrase and add to introduction: "Davoust (1977) showed that the King and Wilson models are members of a general family of models, Gomez-Leyton & Velazquez (2014) generalised the model to non-integer terms. Gieles & Zocchi (2015) added radial velocity isotropy (Eddington 1915, Michie 1963), multiple mass components (Da Costa & Freeman 1976, Gunn & Griffin 1979)"

Balbinot & Gieles (2018) conducted a study of MW GC mass

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[1] `https://people.smp.uq.edu.au/HolgerBaumgardt/globular`, version Jan. 2020

evolution along their orbit in the MWPotential2014, using Galpy for orbit integrations coupled to the emacss (Alexander & Gieles 2012; Alexander et al. 2014; Gieles et al. 2014) code for the GC mass evolution. The initial conditions for the orbit realisations were compiled from the literature before *Gaia* DR2. The authors calculate the initial mass of MW GCs, mass loss, and Jacobi radii.

## 3 SIMULATIONS

Various options

- nbody6 (Aarseth 2003, 2010)
- nbody6tt (Renaud et al. 2011; Renaud 2015; Renaud & Gieles 2015)
  - "Mode A: the tidal information is extracted from a galaxy or cosmology simulation, in the form of tidal tensors, along one orbit. This method is described in (Renaud et al. 2011)"
  - "Mode B: the user defines a numerical function which takes position and time as arguments, and returns the galactic potential. This method is described in (Renaud & Gieles 2015)"
- ICs with McLuster (Kuepper et al. 2011; Küpper et al. 2011)
- galpy (Bovy 2015)
  - galpy.potential.ttensor (Webb et al. 2019b)
  - galpy.potential.rtide (Webb et al. 2019b)
  - galpy.potential.to_amuse (Webb et al. 2019a)
  - MWPotential2014 (Bovy 2015)
- amuse (Portegies Zwart et al. 2009, 2013; Pelupessy et al. 2013; Portegies Zwart & McMillan 2018)
- Gadget-2 (Springel et al. 2001; Springel 2005)
- Arepo (Springel 2010; Pakmor et al. 2011; Pakmor & Springel 2013; Pakmor et al. 2016)
- Arepo-public (Weinberger et al. 2019)

Weinberger R. Springel, V., Pakmor, R., 2019, arXiv:1909.04667 (Public release) Pakmor R., Bauer A., Springel, V., 2011, MNRAS, 418, 1392 (Arepo MHD)

## 4 RESULTS

## 5 DISCUSSION

## 6 CONCLUSIONS

The last numbered section should briefly summarise what has been done, and describe the final conclusions which the authors draw from their work.

## ACKNOWLEDGEMENTS

The research was conducted using the Python (van Rossum & de Boer 1991) programming language with the IPython (Perez & Granger 2007) environment. We used the NumPy (van der Walt et al. 2011), SciPy (Virtanen et al. 2020), galpy[2] (Bovy 2015), pynbody (Pontzen et al. 2013) Astropy[3] (Astropy Collaboration et al. 2013, 2018), Astroquery (Ginsburg et al. 2019), emcee (Foreman-Mackey et al. 2013), and corner (Foreman-Mackey 2016) packages. Furthermore, we use the amuse (Portegies Zwart et al. 2009, 2013; Pelupessy et al. 2013; Portegies Zwart & McMillan 2018) framework. Plots were generated using Matplotlib (Hunter 2007).

[2] https://github.com/jobovy/galpy
[3] https://www.astropy.org

## REFERENCES


Aarseth S. J., 2003, Gravitational N-Body Simulations
Aarseth S. J., 2010, Gravitational N-Body Simulations
Aguilar L. A., White S. D. M., 1985, ApJ, 295, 374
Aguilar L. A., White S. D. M., 1986, ApJ, 307, 97
Alexander P. E. R., Gieles M., 2012, MNRAS, 422, 3415
Alexander P. E. R., Gieles M., Lamers H. J. G. L. M., Baumgardt H., 2014, MNRAS, 442, 1265
Astropy Collaboration et al., 2013, A&A, 558, A33
Astropy Collaboration et al., 2018, AJ, 156, 123
Balbinot E., Gieles M., 2018, MNRAS, 474, 2479
Baumgardt H., 2017, MNRAS, 464, 2174
Baumgardt H., Hilker M., 2018, MNRAS, 478, 1520
Baumgardt H., Hilker M., Sollima A., Bellini A., 2019, MNRAS, 482, 5138
Bellini A., et al., 2014, ApJ, 797, 115
Bovy J., 2015, ApJS, 216, 29
Claydon I., Gieles M., Zocchi A., 2017, MNRAS, 466, 3937
Claydon I., Gieles M., Varri A. L., Heggie D. C., Zocchi A., 2019, MNRAS, 487, 147
Dalgleish H., et al., 2020, MNRAS, 492, 3859
Foreman-Mackey D., 2016, The Journal of Open Source Software, 24
Foreman-Mackey D., Hogg D. W., Lang D., Goodman J., 2013, PASP, 125, 306
Gaia Collaboration et al., 2016a, A&A, 595, A1
Gaia Collaboration et al., 2016b, A&A, 595, A2
Gieles M., Renaud F., 2016, MNRAS, 463, L103
Gieles M., Zocchi A., 2015, MNRAS, 454, 576
Gieles M., Zocchi A., 2018, MNRAS, 474, 3997
Gieles M., Portegies Zwart S. F., Baumgardt H., Athanassoula E., Lamers H. J. G. L. M., Sipior M., Leenaarts J., 2006, MNRAS, 371, 793
Gieles M., Alexander P. E. R., Lamers H. J. G. L. M., Baumgardt H., 2014, MNRAS, 437, 916
Ginsburg A., et al., 2019, AJ, 157, 98
Gnedin O. Y., 2003, ApJ, 582, 141
Hilker M., Baumgardt H., Sollima A., Bellini A., 2020, in Bragaglia A., Davies M., Sills A., Vesperini E., eds, IAU Symposium Vol. 351, IAU Symposium. pp 451–454 (arXiv:1908.02778), doi:10.1017/S1743921319006823
Hunter J. D., 2007, Computing in Science and Engineering, 9, 90
Kamann S., et al., 2018, MNRAS, 473, 5591
King I. R., 1966, AJ, 71, 64
Kruijssen J. M. D., Pelupessy F. I., Lamers H. J. G. L. M., Portegies Zwart S. F., Icke V., 2011, MNRAS, 414, 1339
Kuepper A. H. W., Maschberger T., Kroupa P., Baumgardt H., 2011, McLuster: A Tool to Make a Star Cluster, Astrophysics Source Code Library (ascl:1107.015)
Küpper A. H. W., Maschberger T., Kroupa P., Baumgardt H., 2011, MNRAS, 417, 2300
Lindegren L., et al., 2018, A&A, 616, A2
Miocchi P., et al., 2013, ApJ, 774, 151
Pakmor R., Springel V., 2013, MNRAS, 432, 176
Pakmor R., Bauer A., Springel V., 2011, MNRAS, 418, 1392
Pakmor R., Springel V., Bauer A., Mocz P., Munoz D. J., Ohlmann S. T., Schaal K., Zhu C., 2016, MNRAS, 455, 1134
Pelupessy F. I., van Elteren A., de Vries N., McMillan S. L. W., Drost N., Portegies Zwart S. F., 2013, A&A, 557, A84
Perez F., Granger B. E., 2007, Computing in Science and Engineering, 9, 21
Pontzen A., Roškar R., Stinson G., Woods R., 2013, pynbody: N-Body/SPH analysis for python (ascl:1305.002)

Portegies Zwart S., McMillan S., 2018, Astrophysical Recipes; The art of AMUSE, doi:10.1088/978-0-7503-1320-9.
Portegies Zwart S., et al., 2009, New Astron., 14, 369
Portegies Zwart S., McMillan S. L. W., van Elteren E., Pelupessy I., de Vries N., 2013, Computer Physics Communications, 184, 456
Renaud F., 2015, nbody6tt: Tidal tensors in N-body simulations, Astrophysics Source Code Library (ascl:1502.010)
Renaud F., Gieles M., 2015, MNRAS, 448, 3416
Renaud F., Gieles M., Boily C. M., 2011, MNRAS, 418, 759
Sollima A., Baumgardt H., 2017, MNRAS, 471, 3668
Sollima A., Baumgardt H., Hilker M., 2019, MNRAS, 485, 1460
Spitzer Jr. L., 1958, ApJ, 127, 17
Spitzer L., 1987, Dynamical evolution of globular clusters
Springel V., 2005, MNRAS, 364, 1105
Springel V., 2010, MNRAS, 401, 791
Springel V., Yoshida N., White S. D. M., 2001, New Astron., 6, 79
Trager S. C., King I. R., Djorgovski S., 1995a, AJ, 109, 218
Trager S. C., King I. R., Djorgovski S., 1995b, AJ, 109, 1912
Virtanen P., et al., 2020, Nature Methods, 17, 261
Watkins L. L., van der Marel R. P., Bellini A., Anderson J., 2015, ApJ, 803, 29
Webb J. J., Reina-Campos M., Kruijssen J. M. D., 2018, arXiv e-prints, p. arXiv:1812.00014
Webb J. J., Price-Jones N., Bovy J., Portegies Zwart S., Hunt J. A. S., Mackereth J. T., Leung H. W., 2019a, arXiv e-prints, p. arXiv:1910.01646
Webb J. J., Bovy J., Carlberg R. G., Gieles M., 2019b, MNRAS, 488, 5748
Weinberger R., Springel V., Pakmor R., 2019, arXiv e-prints, p. arXiv:1909.04667
Wilson C. P., 1975, AJ, 80, 175
de Boer T. J. L., Gieles M., Balbinot E., Hénault-Brunet V., Sollima A., Watkins L. L., Claydon I., 2019, MNRAS, 485, 4906
van Rossum G., de Boer J., 1991, CWI Quarterly, 4, 283
van der Walt S., Colbert S. C., Varoquaux G., 2011, Computing in Science and Engineering, 13, 22

## APPENDIX A: SIMULATIONS

This paper has been typeset from a TEX/LATEX file prepared by the author.

| GC | model | N | $\epsilon$ | dt | $\eta$ | seed |
|---|---|---|---|---|---|---|
| NGC 104 | King | $10^3$ | 0.1 | 0-0.01 | 0.025 | 1337 |
| NGC 104 | King | $10^4$ | 0.1 | 0-0.01 | 0.025 | 1337 |
| NGC 104 | King | $10^4$ | 1.0 | 0-0.01 | 0.025 | 1337 |
| NGC 104 | King | $10^4$ | 0.01 | 0-0.01 | 0.025 | 1337 |
| NGC 104 | King | $10^5$ | 0.1 | 0-0.01 | 0.025 | 1337 |