White Dwarfs as Probes of Fundamental Physics: Tracers of Planetary, Stellar and Galactic Evolution
Proceedings IAU Symposium No. 357, 2019
M. A. Barstow, S. J. Kleinman, J. L. Provencal & L. Ferrario, eds.
doi:10.1017/S1743921320000459

Realistic models of Globular Clusters with white dwarfs, neutron stars and black holes using GPU supercomputer

Bhusan Kayastha[1,2,3], Long Wang[4,5], Peter Berczik[2,3,6], Xiaoying Pang[7], Manuel Arca Sedda[3], Albrecht Kamlah[8] and Rainer Spurzem[2,3,9]

[1]University of Chinese Academy of Sciences, 19A Yuquanlu, Shijingshan District, Beijing 100049, China
email: kayastha@nao.cas.cn

[2]National Astronomical Observatories & Key Laboratory of Computational Astrophysics, Chinese Academy of Sciences, 20A Datun Road, Chaoyang District, Beijing 100101, China

[3]Astronomisches Rechen-Institut, Zentrum für Astronomie, University of Heidelberg, Mönchhofstrasse 12-14, 69120 Heidelberg, Germany

[4]Department of Astronomy, School of Science, The University of Tokyo, 7-3-1 Hongo, Bunkyo-ku, Tokyo, 113-0033, Japan

[5]RIKEN Advanced Institute for Computational Science, 7-1-26 Minatojima-minami-machi, Chuo-ku, Kobe, Hyogo 650-0047, Japan

[6]Main Astronomical Observatory, National Academy of Sciences, Kyiv, Ukraine

[7]Department of Mathematical Sciences, Xi'an Jiaotong-Liverpool University, No.111 Ren'ai Road, Dushu Lake Higher Education Town, Suzhou Industrial Park, Suzhou 215123, China

[8]Institut für Astrophysik, Georg-August-Universität Göttingen, Friedrich-Hund-Platz 1, 37077, Göttingen, Germany

[9]Kavli Institute for Astronomy & Astrophysics, Peking University, Yiheyuan Lu 5, Haidian District, Beijing 100871, China

Abstract. We present some results from the DRAGON simulations, a set of four direct N-body simulations of globular clusters (GCs) with a million stars and five percent initial (primordial) binaries. These simulations were undertaken with the NBODY6++GPU code, which allowed us to follow dynamical and stellar evolution of individual stars and binaries, formation and evolution of white dwarfs, neutron stars, and black holes, and the effect of a galactic tidal field. The simulations are the largest existing models of a realistic globular cluster over its full lifetime of 12 billion years. In particular we will show here an investigation of the population of binaries including compact objects (such as white dwarfs - cataclysmic variables and merging black hole binaries in the model as counterparts of LIGO/Virgo sources); their distribution in the cluster and evolution with time.

Keywords. globular clusters, kinematics and dynamics - stars, black holes, gravitational waves

1. Introduction

About 150 globular clusters orbit the Milky Way but more massive galaxies can have over 10,000 gravitationally bound globular clusters. As their stars have mostly formed at the same time but with different masses, globular clusters are ideal laboratories for studies of stellar dynamics and stellar evolution. Our direct N-body (DRAGON) simulations were carried out using the code NBODY6++GPU (Wang *et al.* 2015). This code is designed for an accurate computation of the motion of many bodies (e.g. in star clusters, planetary systems, galactic nuclei) under their mutual Newtonian gravity. It originates from the family of N-body codes initiated by Asrseth (1963, 1999). Even though its asymptotic complexity scales with N^2, where N is the number of particles, the code is much more efficient than any brute-force approach due to a number of important numerical and physical features (Aarseth 2003), such as a fourth order prediction-correction method using a Hermite scheme on only two points in time, hierarchical block time-steps, Kustaanheimo-Stiefel (KS) and Chain regularization of close encounters and few body sub-systems, and an Ahmad-Cohen neighbour scheme (Ahmad & Cohen 1974), which splits the gravitational force on each particle into a component originating from neighbours (irregular force) and another one from more distant particles (regular force). Each particle has two time steps, one connected with the irregular force and another one (generally much larger) for the regular force. Only the regular force computation scales with N^2 asymptotically. This algorithm has a very similar structure to smoothed particle hydrodynamics (SPH). Single and binary stellar evolution is implemented in these N-body codes using the standard recipes described by Hurley, Pols & Tout (2000) and Hurley, Tout & Pols (2002), see also Hurley (2005), with further improvements to take into account fallback at supernova explosions and stellar winds of massive stars (Belczynski *et al.* 2002) as well as neutron star kicks at formation due to Hobbs *et al.* (2005). We use the version NBODY6++GPU of the code, which has parallelization across many computer nodes (using MPI), GPU acceleration for general purpose graphical computing devices (on many nodes, using CUDA) and thread level parallelization on local multi-core CPUs (using OpenMP). Readers who are interested in more technical details are referred to (Spurzem 1999), Berczik *et al.* (2013), and Wang *et al.* (2015). All simulations were performed on the "Hydra" GPU cluster of the Max-Planck Computing and Data Facility (MPCDF), Germany. For each simulation, 8 nodes with a total of 160 Intel Xeon E5-2650 cores and 16 NVIDIA K20m GPUs were used.

2. Results

Figure 1 presents the Hertzsprung-Russell diagram of the Dragon Simulations up to 12Gyr. BSE and SSE stand for Binary Stellar Evolution and Single Stellar Evolution respectively. The zero-age main sequence is along the top-left to lower right diagonal; above the main sequence turnoff there are subgiants, red giants and supergiants seen, as a function of the age of the stellar population. In the lower left cooling white dwarfs are found. The scattered points between white dwarfs and the main sequence are the potential candidates for the cataclysmic variable stars (CVs) .The composite effective temperature for binaries is calculated as flux weighted average of the two binary members.

Figure 2 presents the mock color image (BVI) of all stars of a simulated globular cluster (central image covering about 60 pc) after 12 billion years of evolution. The surrounding panels highlight the different stellar types (from top left): main sequence stars (MS), red giants (RG) dominating the light, invisible black holes (BH), binary stars (Binary), white dwarfs (WD) and asymptotic giant branch stars (AGB). The white dwarfs (about 80,000) are unresolved in this mock image and therefore invisible. Due to the mass-segregation process, BHs form a dense subsystem in the cluster centre, as shown in Figure 2 (panel labelled with "BH", red points represent BHs in binaries). Observations of BHs can be achieved only through the effects that they have on stellar companions, via electromagnetic emission, or among themselves, via gravitational radiation, thus from an observational perspective BHs in binary systems are crucial to constrain their "detectability". In DRAGON simulations, we find afew dozens BHs in

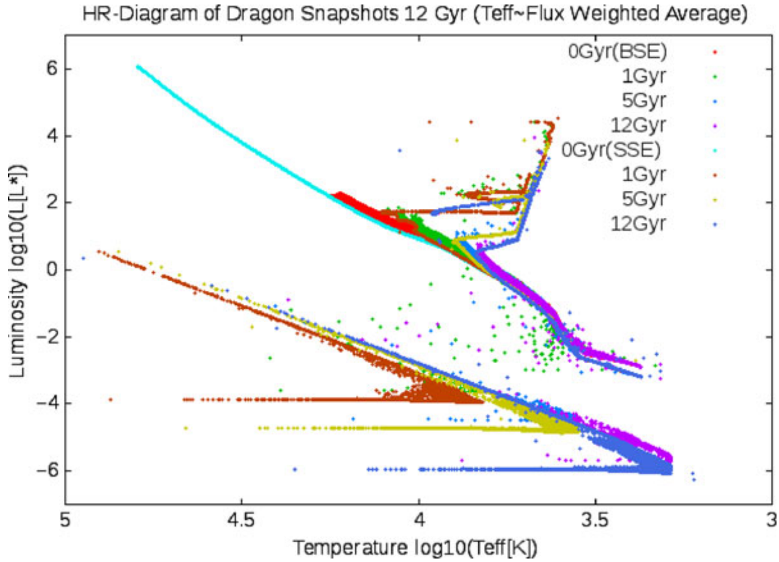

Figure 1. HR Diagram of DRAGON models up to 12Gyr.

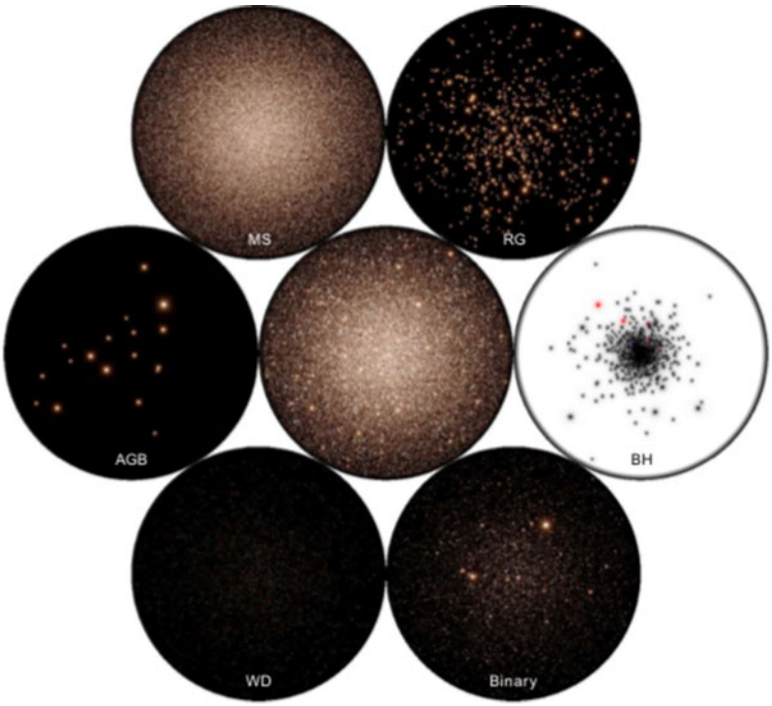

Figure 2. Snapshot of DRAGON models at 12 Gyr as observed in B, V and I bands (Wang *et al.* 2016).

binary systems. As shown in Figure 3, the BH mass spectrum in DRAGON simulations extends from 10 to 32 Msun, with BHs slowly accumulating toward the GC centre over time.

Figure 3. represents the position of the black holes in the globular cluster with respect to the density center. Black holes with 15-20 solar masses are kicked away from the

https://doi.org/10.1017/S1743921320000459 Published online by Cambridge University Press

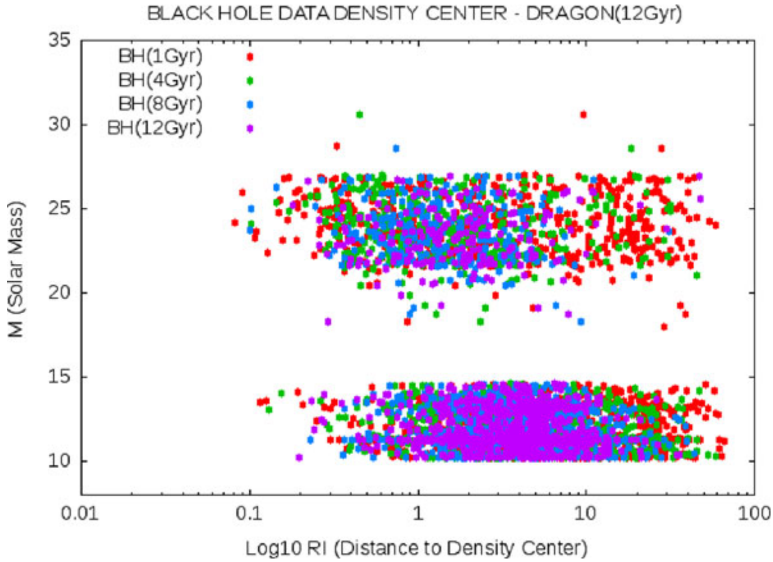

Figure 3. Position of the Black Holes from the density center in the DRAGON models up to 12Gyr.

system because of the natal kicks. Here we can see the black holes are being accumulated more and more towards the density center with time. The dynamical evolution of the central regions of the simulated clusters is dominated by hundreds of single and binary stellar mass black holes.

3. Summary & Discussions

In this paper we present the DRAGON globular cluster models which are evolved from the initial phase after gas removal up to 12 Gyr. The DRAGON clusters are four realistic direct N-body simulations of GCs with initially one million stars, including 5 % primordial binaries, both single and binary stellar evolution and tidal fields together for the first time. We have full information about the modeled cluster, regarding its population and color gradients, its projected stellar densities and kinematic properties of the luminous and compact objects. Some "gravitational wave events" observed in the Dragon simulations are in fair agreement with real LIGO/Virgo detections. Unfortunately, comparison with faster, but more approximate Monte Carlo (MOCCA) dynamical models and with a population synthesis model for galactic field binary populations shows that we cannot yet distinguish the origin of LIGO/Virgo sources (clusters or field). More simulations are required for that goal. The results will be published soon in the paper "Intrinsic Gravitational Wave Emission for Ligo/Virgo from Direct Nbody Models of Star Clusters" (Spurzem *et al.* 2020). The DRAGON simulations were done before the detection of the gravitational wave events by LIGO/Virgo so some methods and recipes used in our codes are outdated. Recently we are ready with the updated version of the NBODY6++GPU code, the main changes include the new mass fallback prescription at supernova explosions and stellar winds of massive stars (Belczynski *et al.* 2019) with low kicks at formation to electron capture supernova (Gessner & Janka 2018) to retain some neutron stars in the cluster. Results from an updated version of the NBODY6++GPU code able to interpret new astronomical discoveries on neutron stars, black holes and gravitational waves will be presented in a series of forthcoming papers.

Acknowledgements

This work has been supported by the Chinese National Science Foundation Project No. 11673032 (RS) & Sino-German Cooperation Project (No. GZ 1284). B.K. would like to thank CAS-TWAS President's PhD Fellowship Programme of the Chinese Academy of Sciences & The World Academy of Sciences, International Astronomical Union for the travel grant to attend IAUS 357. L.W. thanks the financial support from JSPS International Research Fellow (School of Science, The university of Tokyo). X.Y.P. sends her gratitude to the research development fund of Xi'an Jiaotong Liverpool University, RDF-18-02-32. M.A.S. acknowledges financial support by the Alexander von Humboldt Foundation.

References

Aarseth, S. J. 2003, *Gravitational N-Body Simulations*, Cambridge University Press
Ahmad, A. & Cohen, L. 1974, *ApJ*, 188, 469
Aarseth, S. J. 1963, *MNRAS*, 126, 223
Aarseth, S. J. 1999, *PASP*, 111, 1333
Aarseth, S. J. 2012, *MNRAS*, 422, 841
Belczynski, K., Kalogera, V., & Bulik, T. 2002, *ApJ*, 572, 407
Belczynski, K. *et al.* 2019, *ApJ*, 714, 1217
Berczik, P, *et al.* 2013, Third International Conference "High Performance Computing", HPC-UA 2013, p. 52–59
Gessner, A. & Janka, H-T, 2018, *ApJ*, 865, 61
Hobbs, G., Lorimer, D. R., Lyne, A. G., & Kramer, M. 2005, *MNRAS*, 360, 584
Huang S., Spurzem R., & Berczik P. 2015, *arXiv*, arXiv:1508.02510
Hurley, J. R. 2005, *MNRAS*, 363, 315
Hurley, J. R., Pols, O. R., & Tout, C. A. 2000, *MNRAS*, 315, 543
Hurley, J. R., Tout, C. A., & Pols, O. R. 2002, *MNRAS*, 329, 897
Hurley, J. R., Pols, O. R., Aarseth, S. J., & Tout, C. A. 2007, *MNRAS*, 363, 292
King, I. R. 1996, *AJ*, 71, 64
Kouwenhoven, M. B. N., Brown, A. G. A., Portegies, Zwart S. F., & Kaper, L. 2007, *A&A*, 474, 77
Kroupa, P. 1995, *MNRAS*, 277, 1491
Kroupa, P. 2001, *MNRAS*, 322, 231
Nitadori, K. & Aarseth, S. J. 2012, *MNRAS*, 424, 545
Spurzem, R. 1999, *JCoAM*, 109, 407
Spurzem, R. & Aarseth, S. J. 1996, *MNRAS*, 282, 19
Spurzem, R. *et al.* 2020, in press
Wang, L., Spurzem, R., Aarseth, S., Nitadori, K., Berczik, P., Kouwenhoven, M. B. N., & Naab, T. 2015, *MNRAS*, 450, 4070
Wang, L., Spurzem, R., Aarseth, S., Giersz, M., Askar, A., Berczik, P., Naab, T., Schadow, R., & Kouwenhoven, M. B. N. 2016, *MNRAS*, 458, 1450

https://doi.org/10.1017/S1743921320000459 Published online by Cambridge University Press