THE UNIVERSITY of EDINBURGH

School of Mathematics
School of Physics and Astronomy
University of Edinburgh
Scotland, UK
Email: anna.varri@ed.ac.uk
Tel: +44 (0)131-6688-465

May 3, 2023

Professor Leszek Zdunik
Chair of the Committee
Professor Rodolfo Smiljanic
Committee Secretary

Centrum Astronomiczne im. Mikołaja Kopernika
Polskiej Akademii Nauk
ul. Bartycka 18
00-716 Warszawa

Mr Agostino Leveque

Extra Galactic Globular Cluster machinery based on MOCCA code for Star Cluster simulations

The content of Mr Leveque's doctoral thesis offers a valuable contribution to field of theoretical astrophysics, with emphasis on the area of stellar dynamics. Specifically, Chapters 2, 3, 4, and 5 offer tangible evidence of original scientific developments, i.e. solutions to scientific problems of astrophysical interest, as I will discuss below. Chapter 1 also offers appropriate evidence of Mr Leveque's general knowledge in the subject area. Finally, by providing an outlook of future research prospects, Chapter 6 and 7 further demonstrate his ability to independently conduct scientific work.

At the heart of the thesis lies the development of a population synthesis methodology ("MASinGa") that is based on a combination of a semi-analytical approach to study the dynamical evolution of star clusters, together with the quantitative results of a large collection of about 2000 Monte Carlo models (MOCCA-Survey Database I, Giersz et al. 2019).

Refreshingly, appropriate care is given to a discussion of the general limitations of the Monte Carlo (MOCCA, Giersz et al. 2013) modelling approach. Since the computation of direct N-body models of realistic globular star clusters (i.e. with $N \geq 10^6$ stars) is still prohibitively expensive to be used to conduct comprehensive parameter explorations, nowadays orbit-average methods are still a necessity. The advantages resulting from these methods must, therefore, always be accompanied by a critical assessment of their drawbacks - as it is done in the present thesis manuscript (Chapter 1).

The MASinGa – Modelling Astrophysical Systems in GAlaxies – methodology was first introduced and implemented to study the infall and merger of star clusters onto their host galaxy center, as part of the nuclear star cluster formation and growth. While the code was already in existence in a somewhat embryonic form before the start of this thesis (Arca-Sedda and Capuzzo-Dolcetta, 2014b; Arca-Sedda et al., 2015), there is clear evidence that it has been developed in its fully-fledged form in the context of Mr Leveque's doctoral research activities. This methodology is described in detail at the end of the first Chapter, which also provides a useful reader's guide, in preparation to its application to the subsequent science cases.

The results presented in Chapters 2,3,4 are mainly concerned with the characterisation of the dynamical evolution of the population of globular clusters in the Milky Way, with further extensions to the one of the Andromeda galaxy. Chapter 2 defines the ground work: within the MOCCA-Survey Database I, Mr Leveque identifies a set of models which are consistent with the properties of Galactic globular clusters (at different stages of their dynamical evolution), but as observed from an extra-galactic perspective. Chapter 3 compares the results obtained via the MASinGa methodology with the data corresponding to the models identified in Chapter 2, for both the Milky Way and Andromeda star cluster populations. In Chapter 4, the comparison is further specified to the investigation of the properties of globular clusters harbouring a stellar-mass black hole subsystem, an intermediate-mass black hole, or neither of those. This area of study is of topical interest to the community, thanks to its immediate implications for gravitational wave astrophysics. Mr Leveque shows that over 80% of merging binary black holes are formed by dynamical interactions, while the the remaining 20% merging binary black holes appear to come from the evolution of primordial binaries. Consequently, Mr Leveque reports values for the binary black hole merger rate in the local Universe within the range $1.0 - 23$ yr^{-1} Gpc^{-3}, depending on the assumptions about the local galaxy number density.

Finally, Chapter 5 is devoted to a different topic, i.e. the study of the dynamics of the gas embedded in a star cluster, during its initial stages of evolution. This investigation has been conducted by integrating an existing implementation of the Monte Carlo (MOCCA) approach, within the AMUSE software framework (Portegies Zwart & McMillan 2018) – an effort which presents several non-trivial technical aspects. Mr Leveque validates this new approach by showing that the results for the time evolution of mass content and Lagrangian radii are in good agreement with those obtained with N-body simulations of comparable nature. In addition, a new survey of simulations which explore the evolution of globular clusters with up to $N = 500000$ stars (for a range of different star formation efficiencies and half-mass radii) is presented. In turn, this study identifies which physical conditions lead to the clusters' dissolution or survival, after their early evolutionary phase. Ultimately, this exploration constitutes an essential stepping stone to understand the physical conditions which are necessary to yield the formation of multiple stellar populations in globular clusters, a phenomenon which is still puzzling the community.

All chapters 2-5 have already been presented as articles accepted for publication in the international journal "Monthly Notices of the Astronomical Society" – this is an impressive accomplishment and speaks volume about Mr Leveque's work ethics and abilities.

The manuscript is appropriately structured, complete, and contains only minor presentational flaws. My only optional practical suggestion would be to consider enriching the Conclusions (Chapter 7), which, currently, are mostly focused on the implications of the results from Chapter 4 on black hole demographics. The thesis is very rich, and some other highlights, especially from Chapter 5, deserve be mentioned as well!

Summing up, I consider the doctoral thesis of Mr Agostino Leveque to be a valuable contribution and to meet the criteria prescribed by the law for a doctoral dissertation. Therefore, I request that this dissertation is admitted to a public defense.

Yours sincerely,

Anna Lisa Varri

Anna Lisa Varri
UKRI Future Leaders Fellow in Mathematical Astrophysics