The Effects of Binary Stars on Recovered Remnant Populations in Globular Clusters

by

Peter Smith

A THESIS SUBMITTED IN PARTIAL FULFILMENT OF
THE REQUIREMENTS FOR THE DEGREE OF

BACHELOR OF SCIENCE

in

Honours Astrophysics

(Department of Astronomy and Physics, Dr. Vincent Hénault-Brunet supervising faculty)

. . . .

. . . .

. . . .

. . . .

. . . .

SAINT MARY'S UNIVERSITY

January 18, 2022

Abstract

THE EFFECTS OF BINARY STARS ON RECOVERED REMNANT POPULATIONS IN GLOBULAR CLUSTERS

by *Peter Smith*

submitted on January 18, 2022:

Abstract Here

Contents

List of Figures

List of Tables

Chapter 1

Introduction

Peter: I'm thinking an intro to globular clusters, then to modelling GCs with discussion of binaries, then to observations of binaries in GC

1.1 Globular Clusters

Globular clusters (GCs) are dense, spheroidal collection of stars bound by their own self-gravity. GCs are found in most galaxies, with the Milky Way hosting roughly 150, mostly located in the outer halo. GCs typically represent some of the oldest stellar populations in the universe and are usually in excess of 10 billion years old. Globular clusters were thought to have formed from a single giant molecular cloud, resulting in a single coeval population of star with identical abundances. While modern observation shave revealed that many clusters in fact have multiple independent population with difference elemental abundances, most globular clusters are still well-approximated by a single simple stellar population.

The dynamics of a cluster are almost entirely described by the gravitational interactions between object in the cluster.

Any nice review paper I can cite or something similar?

Mention mass segregation

1.1.1 Binaries in Globular Clusters

In general, the binary systems found within present-day clusters differ significantly from the field binaries that are more easily observed. In particular, we expect to little no long-period binaries, on account of them being ionized by the frequent interactions with other cluster members. We frequently use the terms ”hard” and ”soft” to describe binaries where ”soft binaries” have a binding energy comparable to the average kinetic energy of a cluster member while ”hard binaries” have larger binding energy. Due to the frequent interactions within clusters we expect that all soft binaries have long since been ionized by the present-day leaving only a population of hard binaries with a truncated period distribution compared to field binaries. Peter: Cite some papers here

Binary Burning: Chatterjee et al. (2013)

Black Hole Burning: Kremer et al. (2019)

Some dynamical effects of binaries, mention that we're focusing on hard binaries that we can treat as point masses, not so much the long-period binaries that provide significant energy through hardening during interactions.

The primary way that binaries can effect the dynamics of a cluster is through three-body interactions with other cluster members. When a single star (or another binary) interacts with a binary system at a close enough range, the binary system will ”tighten”, imparting some of its energy to the ejected star. Through this process binary systems can act as a reserve of kinetic energy for a cluster and are thought to be one of the primary mechanisms through which core-collapse is halted in some clusters (Chatterjee et al., 2013).

The second way that binaries can impact the dynamics of a cluster is simply due to their higher mass when compared to single stars. Because binaries are tightly bound, for all interaction except for the very closest, they effectively act as a single point mass equal to the sum of each component's mass. In this way, binaries can affect cluster dynamics in much the same way that a large population of white dwarfs or neutron star would (see for example Kremer et al. (2021)) Peter: discuss what these effects would be. Through simple two-body interactions with other cluster members, binaries will begin to migrate to the central regions of the cluster due to mass segregation. This predicted increase in binary fraction as you get closer to the centre of a cluster is also seen in observations Peter: cite something here . Peter: maybe refer to the effects of black hole burning? Kremer et al. (2019) Check some of those "Binary Burning" papers.

1.1.2 Observations of Binary Stars in Globular Clusters

In general, there are two methods used to detect binaries within globular clusters: high-precision photometric observations and radial velocity surveys.

High-precision photometry can be used to detect binaries along the main sequence which have a significant difference in the mass of their components (typically these systems have a mass ratio, q, larger than 0.5). These systems will appear to be raised above the main-sequence when plotted on a colour-magnitude diagram as their colour will match that of a typical main-sequence star however their luminosity will be the sum of both components. Figure 1.1.2 shows the main-sequence of the cluster NGC 2298, the binary stars in this cluster are visible above the main-sequence according to their mass ratio. Milone et al. (2012) performed high-precision photometry on several globular clusters using the Hubble Space Telescope's (HST) Advanced Camera for Surveys and was able to place strong constraints on the binary fraction for binaries with a mass ratio above $q = 0.5$. This method allows for large studies of binary populations in GCs without the need for dedicated observations but suffers from an inherent bias towards systems with high mass ratios. Systems with mass ratios below $q = 0.5$ are typically too close to the regular main-sequence to confidently classify as binaries (see Figure 1.1.2). This means that studies which employ this method must assume an underlying mass-ratio distribution if they wish to place any limits on the overall binary fraction of a cluster.

Large-scale campaigns to measure the radial velocities for many stars in a cluster over several epochs are another method which can be used to detect binaries in GCs. Systems which are found to have periodically varying radial velocities can typically be confidently classified as binary systems. Giesers et al. (2019) used the MUSE integral field spectrograph installed at the European Southern Observatory's Very Large Telescope to observe several GCs and reported the results for NGC 3201. Integral field spectrographs provide spatially resolved spectra for the entire field of view of the detector which enables far more time-efficient surveys than previous methods. Because this methods measure radial velocities and periods, it can be used to constrain most of a binary system's orbital parameters allowing us to verify our assumptions Peter:

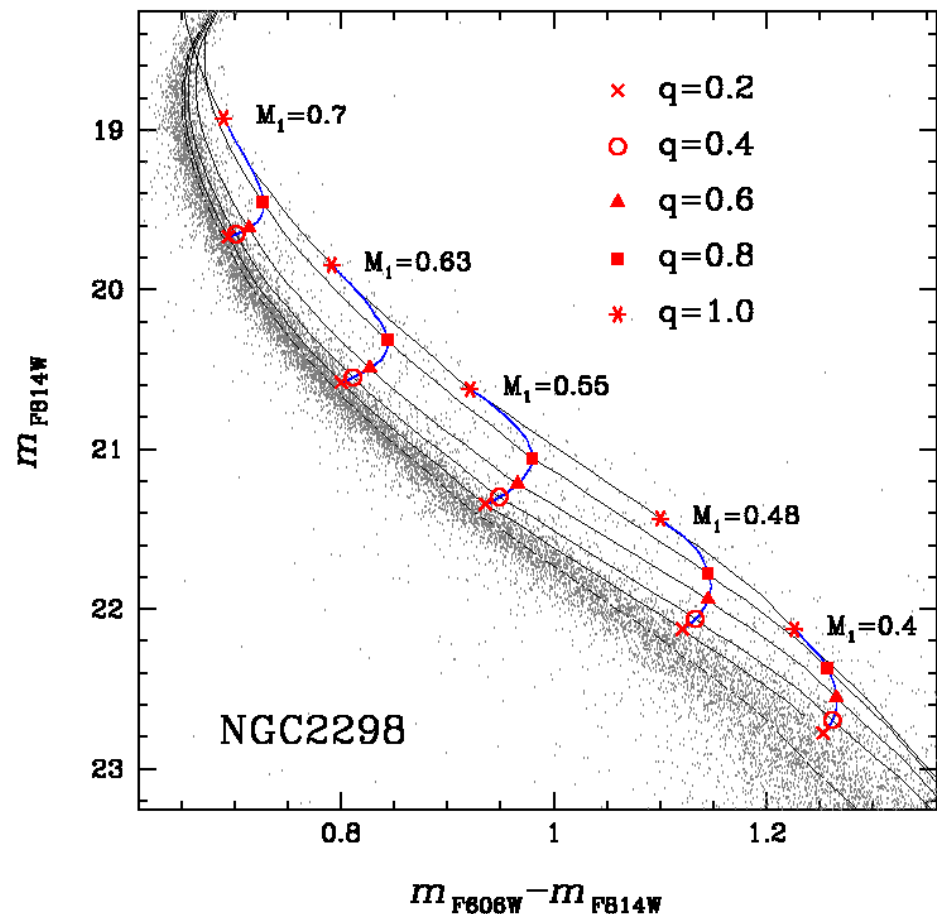

Figure 1.1: Peter: TODO: write proper caption Reproduced from Figure 1 of Milone et al. (2012).

does it validate them? some binaries with periods up to 1000 days there? about the period distributions of binaries in globular clusters. Peter: grab a figure from the MUSE paper with period distribution?

1.2 Modelling Globular Clusters

When modelling globular clusters, there are generally two approaches you can take. The first is to model the entire evolutionary history of the cluster from initial conditions to the present. The most commonly employed versions of these ”evolutionary models” are direct N-body integration (see for example Baumgardt (2017)) which directly calculate the gravitational interactions between each object in the cluster and Monte-Carlo models (see Rodriguez et al. (2021) or Hypki and Giersz (2013)) which approximate the gravitational interactions between object according to the method of Hénon (1971). While these models provide insight into the dynamical history of the cluster, they are very computationally expensive with even the fastest models taking on the order of a day to model a realistic globular cluster (Rodriguez et al., 2021).

The second approach is to model just the present-day conditions of the cluster. These models, which we call ”equilibrium models”, capture none of the dynamical history of the cluster but fully describe the present-day state of the cluster and are orders of magnitude faster to compute with typical models being on the order of a second. The comparative efficiency of these models enables the use of statistical fitting techniques like MCMC or Nested Sampling which would be prohibitively expensive to use with evolutionary models. This means that instead of a computing a grid of models and finding the "best-fitting" model we can instead recover posterior distributions for key cluster parameters.

In this work we use the `LIMEPY` family of models presented by Gieles and Zocchi (2015). Peter: Describe how the models work. In their current implementation, these models assume that all objects within the cluster are single and make no attempt to model the dynamical effects of stellar multiplicity. In this project we adapt these models to incorporate some of the effects of binary stars under the assumption that all long-period binaries have been ionized by the present-day.

Chapter 2

Methods

Chapter 3

Results

Chapter 4

Discussion

Appendix A

Appendix

Bibliography

H. Baumgardt. N-body modelling of globular clusters: Masses, mass-to-light ratios and intermediate-mass black holes. *Monthly Notices of the Royal Astronomical Society*, 464(2):2174–2202, jan 2017.

Sourav Chatterjee, Stefan Umbreit, John M. Fregeau, and Frederic A. Rasio. Understanding the dynamical state of globular clusters: Core-collapsed versus non-core-collapsed. *Monthly Notices of the Royal Astronomical Society*, 429(4):2881–2893, mar 2013.

Mark Gieles and Alice Zocchi. A family of lowered isothermal models. *Monthly Notices of the Royal Astronomical Society*, 454(1):576–592, nov 2015.

Benjamin Giesers, Sebastian Kamann, Stefan Dreizler, Tim Oliver Husser, Abbas Askar, Fabian Göttgens, Jarle Brinchmann, Marilyn Latour, Peter M. Weilbacher, Martin Wendt, and Martin M. Roth. A stellar census in globular clusters with MUSE: Binaries in NGC 3201. *Astronomy and Astrophysics*, 632, dec 2019.

M. Hénon. Monte Carlo models of star clusters. *Astrophysics and Space Science*, 13 (2):284–299, oct 1971.

Arkadiusz Hypki and Mirek Giersz. mocca code for star cluster simulations – I. Blue stragglers, first results. *Monthly Notices of the Royal Astronomical Society*, 429(2): 1221–1243, feb 2013.

Kyle Kremer, Nicholas Z. Rui, Newlin C. Weatherford, Sourav Chatterjee, Giacomo Fragione, Frederic A. Rasio, Carl L. Rodriguez, and Claire S. Ye. White Dwarf Subsystems in Core-Collapsed Globular Clusters. *The Astrophysical Journal*, 917 (1):28, aug 2021.

Kyle Kremer, Claire S. Ye, Sourav Chatterjee, Carl L. Rodriguez, and Frederic A. Rasio. The Role of black hole burning in the evolution of dense star clusters. *Proceedings of the International Astronomical Union*, 14(351):357–366, may 2019.

A. P. Milone, G. Piotto, L. R. Bedin, A. Aparicio, J. Anderson, A. Sarajedini, A. F. Marino, A. Moretti, M. B. Davies, B. Chaboyer, A. Dotter, M. Hempel, A. Marín-Franch, S. Majewski, N. E.Q. Paust, I. N. Reid, A. Rosenberg, and M. Siegel. The ACS survey of Galactic globular clusters: XII. Photometric binaries along the main sequence. *Astronomy and Astrophysics*, 540(S241):A16, apr 2012.

Carl L. Rodriguez, Newlin C. Weatherford, Scott C. Coughlin, Pau Amaro Seoane, Katelyn Breivik, Sourav Chatterjee, Giacomo Fragione, Fulya Kıroğlu, Kyle Kremer, Nicholas Z. Rui, Claire S. Ye, Michael Zevin, and Frederic A. Rasio. Modeling Dense Star Clusters in the Milky Way and Beyond with the Cluster Monte Carlo Code. jun 2021.