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

by

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Abstract

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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). Because the models that we will be focusing on do not model individual objects within the cluster we will instead focus of the second way that binaries can effect the dynamics of a cluster.

Because binaries are tightly bound, for all interactions 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 heavy remnants might. Much like black holes and neutron stars, binary systems will migrate to the centre of a cluster due to the effect of mass-segregation. Kremer et al. (2019) found that a central population of black holes can fulfill a similar role to binary systems in halting core collapse by injecting kinetic energy through two-body interactions within the core of the cluster. This same mechanism could apply with tightly-bound binary systems that have mass-segregated to the centre of the cluster. 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, sollima? giersz? .

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

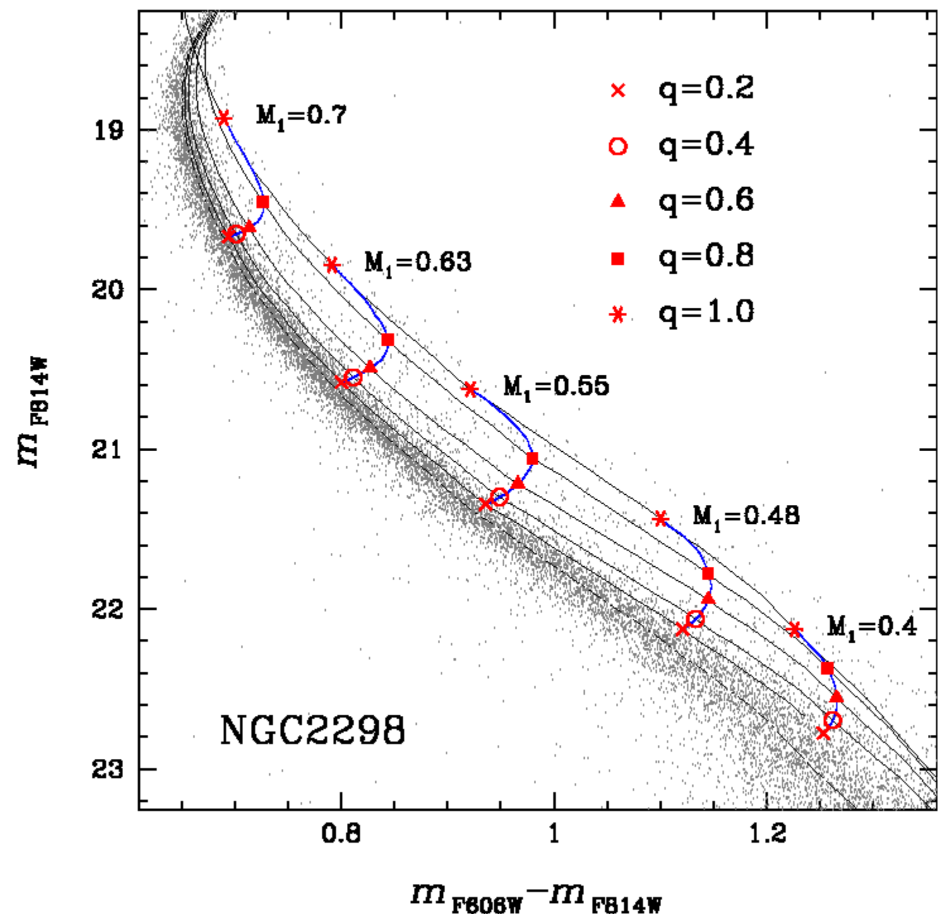

Figure 1.1: Peter: TODO: write proper caption Reproduced from Figure 1 of Milone et al. (2012).

of a binary system's orbital parameters allowing us to verify our assumptions Peter: 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

Peter: clean this up

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.

These equilibrium models are much less computationally demanding than evolutionary models (N-body or Monte Carlo models). Their relative efficiency allows us to explore a significantly larger parameter space when fitting the models to observations to constrain the present-day properties of a cluster. In particular, it is worth highlighting that by using equilibrium models we are able to vary the stellar mass function of the cluster as well as the black hole and remnant retention fractions with more flexibility than what might be possible with evolutionary models, due to the computational cost of computing extensive grids of evolutionary models with many parameters varied in the initial conditions (e.g. various stellar initial mass functions, initial cluster radii, masses, etc.).

The comparative efficiency of these models further 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). 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.

The `LIMEPY` models are a set of distribution function based equilibrium models that are isothermal for the most bound stars near the cluster centre and described by polytropes in the outer regions near the escape energy. The models have been extensively tested against N-body models (Zocchi et al., 2016; Peuten et al., 2017) and are able to effectively reproduce the effects of mass segregation. Their suitability for mass modelling globular clusters has been tested on mock data (Hénault-Brunet et al., 2019) and they have recently been applied to real datasets as well (e.g. Gieles et al., 2018; Hénault-Brunet et al., 2020).

The input parameters needed to compute our models include the central concentration parameter W_0, the truncation parameter g[1], the anisotropy radius r_a which determines the degree of radial anisotropy in the models, δ which sets the mass dependence of the velocity scale and thus governs the degree of mass segregation, and finally the specific mass bins to use as defined by the mean stellar mass (m_j) and total mass (M_j) of each bin, which together specify the stellar mass function. In order to scale the model units into physical units, the total mass of the cluster M and a size scale (the half-mass radius of the cluster r_h) are provided as well.

[1] Woolley models (Woolley, 1954) have $g = 0$, King models (King, 1966) $g = 1$, and Wilson models (Wilson, 1975) $g = 2$.

Chapter 2

Methods

Chapter 3

Results

Chapter 4

Discussion

Appendix A

Appendix

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