The Great Collapse

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CHAPTER 1 Introduction

Stars are the fundamental unit of astronomy. In this thesis I will explore the nature of various types of collapse on stars and star systems.

Stars can be found alone, individual bodies moving through space; or they can be gravitationally bound to one or a few other stars, moving through space together. Of particular interest here are stars in groups of three. Such triple systems can be found in different configurations; the stars may all have orbits, about their collective center of mass, of comparable size in which case the system is very likely to be dynamically unstable due to strong interactions between the stars, though there are some configurations of this type which are stable they occupy a very small fraction of the relevant orbital parameter space. In a hierarchical triple on the other hand, the stars have orbits such that the inner two stars are relatively tightly bound while the third star is much farther away, this *tends* to produce dynamically stable systems.

If one of the stars in a hierarchical triple, or any other stable multiple system, undergoes a supernova—wherein the star's core begins to collapse and then rebounds producing an incredibly powerful explosion—causing the star to almost instantaneously lose the majority of its mass the dynamical stability of the system is placed in jeopardy due to the change in the gravitational force between the stars. This effect in binary systems has been studied many times by Blaauw (1961) and Boersma (1961), Hills (1983), and Tauris and Takens (1998). Complicating matters are the effects of the shell impact on the companion and the supernova kick.

After the supernova the remnant core of the star may become a neutron star, and if that neutron star has a companion which evolves and begins to overflow its Roche lobe causing material to be accreated onto the neutron star it may begin to rotate faster and faster from the transfer of angular moment from the accreating material. This is the suggested formation mechanism for a class of objects called millisecond pulsars. These objects rotate once every few milliseconds.

However, if the supernova progenitor was massive enough, around 20 $M_\odot$, it would not form a neutron star but it would collapse into a stellar mass black hole. There are three astronomically relevant classes of black holes, stellar mass, intermediate mass, and supermassive. Stellar mass black holes have masses <50 or 100 $M_\odot$; supermassive black holes have masses >10^6 $M_\odot$; and intermediate mass black holes have masses between those ranges. Supermassive and stellar mass black hole have been identified with strong constraints placed on their masses, however intermediate mass black holes have never been definitively identified.

Currently there are several intermediate mass black hole (IMBH) candidates; currently the strongest IMBH candidate is the hyperluminous X-ray source HLX-1 with mass estimates generally given to be between some 10^3 and 10^5 $M_\odot$. M82 X-1 is also a strong IMBH candidate with mass estimates ranging from a couple $\times 10^2$ and 10^3 $M_\odot$.

The collapse of star clusters is the result of there being too little kinetic energy relative to potential energy. We know from the virial theorem that in a stable system the time-averaged kinetic energy will be $^1/_2$ the potential energy of the system. If the stars in a cluster have too little kinetic energy, meaning it is subvirial, the system will contract. The inverse is also true, if the stars have too much kinetic energy, supervirial, the system will expand. When a system is subvirial it will experience a radial contraction and a corresponding phase of high density, the collapse, during which time extreme dynamical processes can occur, including violent relaxation.

Violent relaxation was coined by Lynden-Bell (1967) to describe the "violently changing gravitational field of a newly formed galaxy". The theory is rooted in the idea that stars in a collapsing model may be treated as a large set of independent, non-interacting harmonic oscillators. These oscillators treated statistically are expected to find a state of maximum entropy. Thus in a subvirial cluster we would expect to find the effects of violent relaxation.

One possible effect of violent relaxation is very rapid mass segregation[1] of the cluster. Mass segregation has been observed in young clusters, whose age constrains the more common mechanism for mass segregation, i.e. two-body relaxation. It was suggested (Bonnell and Davies 1998) that such rapid mass segregation was not the result of a dynamical mechanism, however this was found to be incorrect by Allison et al. (2009a). What had remained not well understood was when during the collapse, and exactly by what mechanism this rapid dynamical mechanism was occurring.

Two different mechanisms were suggested, which occur at different times

[1] where massive objects are statistically more likely to be found near other massive objects than objects of arbitrary mass

during the collapse. Allison et al. (2009a) first suggested that subvirial collapsing clusters mass segregate more quickly than might be expected due to the dense core formed as the end of the collapse. Whereas, McMillan et al. (2012) claimed that this rapid mass segregation happens not around the time of the “high density bounce”, but rather during the entire collapse via the formation of subclumps which mass segregate independently.

In order to investigate and hopefully gain some understanding of these physical systems we have employed the use of computer simulations. We have used codes that calculate the pair-wise gravitational force between stars, codes that model the evolution of stars, and codes which solves sets of analytic solutions we developed to calculate the effects of a supernova in a hierarchical triple. Most, if not all, of this work would be impossible to complete without efficient codes to run, and at least once we had to develop new methods which were fast enough to run the analysis we needed.

With the exception of Chapter 5 all the simulations presented in this work were run in the AMUSE environment. AMUSE is a modular simulation platform which, through a PYTHON interface, links together to a set of simulation codes. Different codes can easily be used on the same initial conditions, allowing for a fast, simple, and clear test of consistency between codes; AMUSE’s modular nature makes this easy to do, usually requiring a change to only two lines of code.

The benefit of its modular design is not only being able to test, and thus verify, different codes against one another, but also the ease with which one can add additional physics. For example, including stellar evolution in a hydrodynamics simulation is relatively easy compared to having to merge two codes together by hand.

1.1 This Work

1.1.1 Initial Virial Temperature (Chapter 2)

We investigate the effect of the initial virial temperatures on the dynamics of star clusters and find a strong relationship between the initial virial temperature and many dynamical processes. We investigate in depth the likely initial virial temperature of the young cluster R136 along with 15 other young clusters; we find that the most likely value for the initial virial temperature in all of the clusters we tested to be between $\approx$0.18 and 0.25.

1.1.2 Mass Segregation in a Collapsing Cluster (Chapter 3)

Building off of the simulations from Chapter 2 we attempt to isolate the mechanism by which rapid mass segregation occurs in young clusters. In order to measure the mass segregation for the large data sets we had it was necessary to first develop a new method for measuring the systems mass segregation. We detail the increase in accuracy in measuring mass segregation in complex systems as well as the dramatic increase in speed from our new method. After performing a computational experiment we are able to show the greater role the dense part of the collapse plays in rapid mass segregation.

1.1.3 The Number of IMBHs (Chapter 4)

In this chapter we make an estimate of the number of IMBHs within 100 Mpc, based on the nature of HLX-1 and M81 X-1, and stellar evolution simulations. We expect, within the limits of our assumptions, that there should be of order 10^8 IMBHs within that volume. Furthermore, from the results of our simulations we find a constraint on the mass of HLX-1's proposed stellar companion to have a mass between $\approx$10 and 11 $M_\odot$.

1.1.4 Supernova in Hierarchical Star Systems (Chapter 5)

We explore, for the first time, the effect of supernova on higher multiplicity hierarchical systems. In doing so we develop analytical methods to calculate the orbital parameters for systems that remain bound and the runaway velocities for systems that become dissociated after the supernova. We apply these methods to the case of the unusual millisecond pulsar J1903+0327 and confirm that it could have formed from a triple and constrain many of the system's pre-supernova parameters.