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CHAPTER 6 Summary

The fundamental thing in astronomy is the star. Every study in astronomy is based on, in, about, around, or somehow related to stars and their physical processes. This thesis is no different. In particular, I focus on different forms of collapse related to stars and groups of stars.

Most stars are born in groups, and some of these groups can be amazingly massive with many thousands or more stars. As stars form in a group, or cluster, the cluster itself may start to contract, or collapse, and this collapse can lead to interesting systems. As the cluster collapses all the stars begin moving faster as well as ever closer together, this can lead to–among other things–collisions, the formation of binaries or larger sets, and the ejection of stars from the system as they are slingshot outward.

When stars reach the end of their life, having burned all of their nuclear fuel one of only a few things can happen to them. If the star is less than about 8-10 times the mass of our Sun, they will push off most of their material through strong winds and periodic pulsations. If it is more massive it will lose most of its material in a collapse followed by an awe-inspiring explosion called a supernova. If it was a very massive star, more than about 20 times the mass of the Sun, than it might collapse into a black hole after the supernova. Black holes like these are called stellar mass black holes[1], because they are expected to have masses between a few times the mass of our Sun to tens of times the mass of the Sun.

Chapters 2 and 3 of this thesis examine how stars behave when they are born in clusters, while the other two chapters, namely 5 and 4, examine what large stars do when they die. In the former I examine what happens to clusters as the stars are just being born; are the clusters likely to contract as the stars are

[1] Other classes of black holes exist: supermassive black holes are more than about one million times the mass of the Sun and are observed at the center of galaxies. If the mass of a black hole is between about one hundred and one million times the mass of the Sun it would be called an intermediate mass black hole–though no such objects have been definitively identified, currently HLX-1, as discussed in Chapter 4, is the leading candidate for such an object.

formed, and if they are likely to contract, then by how much. I also examine how stars arrange themselves within these clusters; often young clusters are seen to have the most massive stars near the center of the cluster and we have identified the most likely way that happens. In the latter case I make an estimate of the number of intermediate mass black holes that we should expect to be within about 325 million light years from Earth. Finally, in Chapter 5 I show what can happen in a triple star system when one of the stars goes supernova.

All of these studies have been done not primarily by looking into the night sky and observing what happens, but rather by using a computer to simulate what stars will do under the influence of gravity and other physical processes. But why would we use computers and simulations when there are so many stars at which we could point our telescopes?

6.1 The Role of Simulations

Consider, for a moment, that aliens observed Earth and, with their sophisticated technology, they were able to take a photograph containing the image of every living human at one instance in time. From this photograph the aliens would likely work out that most humans are between the ages of 20 and 60 (Earth) years old. The aliens may discover from the photo and clever theories and measurements that the young humans eventually advance to the middle-aged class and that the middle-aged humans advance to the still older class.

While the aliens could learn many things about humans from that photograph of a single moment in time, it stands to reason that they would learn vastly more from a video showing all living humans and their activities during some amount of time. And the longer the video the more and more secrets would be unlocked, allowing them to study not only how humans age and are grouped, but how they migrate from one place to another, and if the video were long enough maybe even how civilizations rise and fall.

Astronomers (human ones at least) have this same difficulty. By using telescopes we have taken photographs (and data) of many stars, and from this information we have pieced together an amazing history of the Universe. We have learned that stars are born often times with siblings, and then they enter a long mid-life phase which is usually very stable, and then they enter a dynamic late-life phase, and finally die in, usually, rather beautiful ways. We have learned, just from our "star snapshot", about galaxies, and cosmic voids, and black holes, and supernova, and on and on. But we can make a video, or an expected video at least, through the use of simulations. Simulations allow us to use a computer, programmed with the laws of physics, and determine what a galaxy might have looked like a million or even a billion years ago. They allow us to see the past Universe in a way that we could not otherwise see, and to extrapolate how the Universe will change in the future which would otherwise require us to observe it for millions of years.

Simulations are not guaranteed to be correct and they should be approached thoughtfully. However, with careful considerations and basic assumptions we can approximate what is and has been happening in Universe near and far. Simulations are a powerful tool for the astronomer, and it is through these theoretical methods that I have performed the work detailed in this thesis.

6.2 Collapsing Clusters

In Chapters 2 and 3 I detail the results from more than 500 simulations of star clusters. Each simulation was started with the stars in that simulation having different velocities than the stars in the other simulations; in some simulations the stars were given so much velocity, kinetic energy, that most of the stars were flung away from the system–traveling too fast for the gravity from the other stars to keep everything bound. In other simulations the stars were given the exact velocity so that no stars were lost and they moved in orbits almost as if they had always been moving in that way, called virial systems; and in other simulations,called cold systems, the stars were given no initial velocity at all and in those simulations the stars immediately started to fall toward the center of the cluster, this is a star cluster in collapse.

6.2.1 Taking a Star Cluster's Temperature

In Chapter 2 I show that the choice of which velocity, kinetic energy, the system is initially given makes a dramatic impact on how the system evolves. Because the simulations had shown the effect of the initial stellar velocity on the evolution of the cluster it became possible to identify the initial stellar velocities of a young cluster if that cluster had been observed in detail.

Somewhere in the Large Magellanic Cloud, a neighboring galaxy, is a very young star cluster called R136. Due to its age and the fact that it has been observed many times R136 proved to be an ideal observational companion to this theoretical study. Comparing the measured radius of the cluster core, the distribution of the stars, the ratio of kinetic to potential energy, and the cluster's age to the simulations we were able to determine the initial velocity of the stars in R136 was most likely between about 0.4 and 0.5 time the velocity they would have been in virial system.

When this analysis was extended to include 15 more young star clusters the most common initial velocity was found to be between 0.6 and 0.7 times the initial velocity in the virial system. If other star clusters are like the ones studied here then we have learned that nature may tend to make star cluster cool, but not cold. However, to fully understand the physics in these star clusters we need to push the simulations even further; we need to consider the physics of gas and dust in the cluster, and just how many stars are initially in binaries, for example. As we add more and more complexity to our simulations, our videos of an alien system, we will find more and more details about just how nature works.

6.2.2 Why do all of the Big Stars Clump Together?

Chapter 3 is about one thing, what causes all of the most massive stars to clump together in young clusters? Young cluster are known to mass segregate, that is the more massive stars tend to be clumped together, but the way they do this so quickly was not understood. Two ideas had been proposed: The first idea was that as the young cluster contracts it becomes very dense, and when they are all very close to each other the most massive stars tend to find the other massive stars and then stay close to one another, due to gravity. The second idea suggested was that is the star cluster contracts, little sub-clusters form and, because of their size, these sub-clusters mass segregate very rapidly and that effect is preserved after all of the sub-clumps had merged.

Because there was so much data to examine in the simulations we needed to develop a new, faster method to measure if, and to what degree, a star system was mass segregated. That was accomplished the new method is orders of magnitude faster than the previous method and its results are more robust.

After developing the new method I was able to design an experiment where I took one simulation and measured the mass segregation of the system at each moment in time for the length of the simulation. Then, after running the simulation again but for only part of the time, I randomly rearranged the masses, being sure to not change the velocity or position of each star, and then finished the simulation. I did this five different times, each time starting from the same, original setup and moving the masses at a different time. Twice I randomly switched the masses while the star cluster was collapsing, twice I randomly rearranged the masses after the collapse, and once I randomly reordered the masses at the moment the system was the most dense.

If the amount of mass segregation did not change significantly after swapping the masses at and after the collapse then either our method was not working or neither proposed idea was correct about how the cluster became mass segregated; this however was not the case.

If, after switching the masses around before the moment the system was its most contracted, the mass segregation *was* significantly changed at the end of the simulation then the second scenario is correct because in that case it matters where the masses are before the deepest moment of the collapse. If however, the mass segregation was *not* significantly changed at the end of the simulation then it means the mass segregation occurs when the system is in the deep part of the collapse and so the first scenario is correct.

The result showed that the first scenario is more correct. If the masses are jumbled before the collapse it makes little to no difference on the final mass segregation of the system. That means the important time, for mass segregation, is when the system is very dense and the time before that when the second proposed idea would be working is of little importance.

6.3 Collapsing Stars

When massive stars die they experience a collapse leading to a supernova and if they are massive enough they may collapse again into a black hole. In Chapter 5 I look at the effect a supernova will have on a system of three or more stars. When a star goes supernova it loses much of its mass and so the gravitational force felt by the other stars is reduced, which can lead to the stars no longer being gravitationally bound to one another. In Chapter 4 I estimate the number of intermediate mass black holes, IMBHs, that should be in the local Universe.

6.3.1 Supernova

It is not uncommon for stars to be found in gravitationally bound groups of two, three or more. If one, or more, of the stars in these small star systems is massive enough to go supernova then there will be a large and sudden loss of mass in the system. This mass loss may cause a previously stable system to become unstable due to the change in the gravitational forces between the stars.

In Chapter 5 we examine triple systems where two stars are close together and the third star is relatively far away, called a hierarchal triple, the two close stars can be approximated as a single star from the perspective of the outer star. Using this method I determine the conditions required for the system to remain stable after the supernova, and inversely which conditions will lead to the stars no longer being bound together.

Using this method I ran simulations to determine if it was possible for the currently observed millisecond pulsar[2] J1903+0327 to have been formed in a triple system which became unstable after a supernova. I was able to determine that the system could form this way and the likely mass of the stars before the supernova. Again, by making use of simulations (a video of some part of the Universe) we are able to learn much more than by observations (a photograph) alone.

[2] A millisecond pulsar is a star with rotates once every few milliseconds (one one-thousandths of a second). They are important for a variety of reasons, including being very accurate as a clock.

6.3.2 Intermediate Mass Black Holes

While we have a strong understanding of many things in the Universe there are many more things we do not understand. An example of something we do not understand are where all Intermediate Mass Black Holes (IMBHs) are. These objects would have a mass between about one hundred and one million times the mass of our Sun, but as of yet an IMBH has not been definitively observed, where as less massive and more massive black hole have been detected. However, there is no good theory as to why nature should not produce these mid-sized black holes so we continue looking for them.

There have been several suggested candidates in the past which turned out to be different types of objects. One possible IMBH, HLX-1, is the strongest candidate to date, with another good candidate in M82 X-1. Using these two candidates as prototypes, and the assumption that they are both in fact IMBHs, I estimate in Chapter 4the number of IMBHs that statistically must be out there in order for these two black holes to observed. In other words, how many IMBHs would we need to have in the nearby Universe in order to detect two?

This estimate is based on assuming why these black holes are visible and finding the likelihood that such a detectable system would form and be observable right now. I found that, given our assumptions, there would need to be around 100 million IMBHs within about 325 million light years. That would mean around 1000 IMBH per galaxy, if there were an equal number per galaxy.