Stellar collisions in young star clusters

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Chapter 1

Introduction

1.1 Stellar collisions in star clusters

Observational data and numerical modelling provide strong evidence that most, if not all, stars form in star clusters (Lada & Lada, 2003; Zinnecker & Yorke, 2007). Star clusters can therefore be viewed as fundamental building blocks of the Universe. There is even tentative observational evidence that the Sun was a member of a star cluster (Looney et al., 2006).

It appears that star clusters are formed in a compact state and with a low star formation efficiency, which is the ratio of the total mass of stars to the total mass of both stars and the remaining gas. Star formation is a continuous process which, in the absence of response from young stars, would probably continue until nearly all the gas is converted into stars. However, young massive stars generate enough energy by means of stellar winds, photo-ionising (ultraviolet) radiation and supernova explosions that star formation is switched off and the left-over gas is completely expelled from the cluster within ten million years. A star cluster is considered to be born at the moment when most of the remaining gas is expelled.

The dynamical evolution of such young star clusters is very rich. Since the cluster is abundant in massive stars, the effect called *dynamical friction* heavily affects the motion of stars with the mass much higher than the average mass of stars in the surroundings. A massive star deflects trajectories of low-mass stars, and this generates a wake behind it (Fig.1.1). The net result is that stellar density is higher behind this massive star, and therefore there is a net gravitational force which pulls the star back. As with satellites orbiting the Earth, such a pull results in the decay of the orbit, and after some time, the massive star will reach the central regions of the star cluster, which is called the core. The speed of descent is proportional to the mass of the star. Hence, the most massive stars in a cluster will be the first to reach the core. The cumulative effect of dynamical friction is that the stars are segregated by mass, with high-mass stars concentrated in the centre. Such a cluster is said to be mass-segregated. (Fig.1.2).

Star clusters can also be considered as thermal systems, where central regions are hotter (stars have on average higher kinetic energy) than the

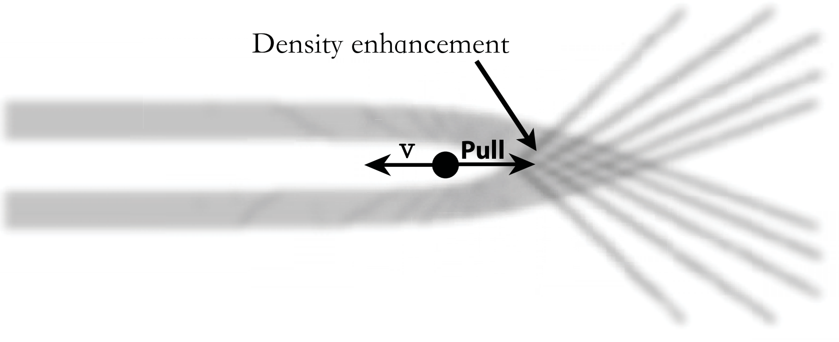

Figure 1.1: *As a massive object moves through the field of low-mass stars, the trajectories of these stars deviate from a straight line. This results in the excess of low-mass stars behind the object, which generates a net gravitational pull which slows the object down.*

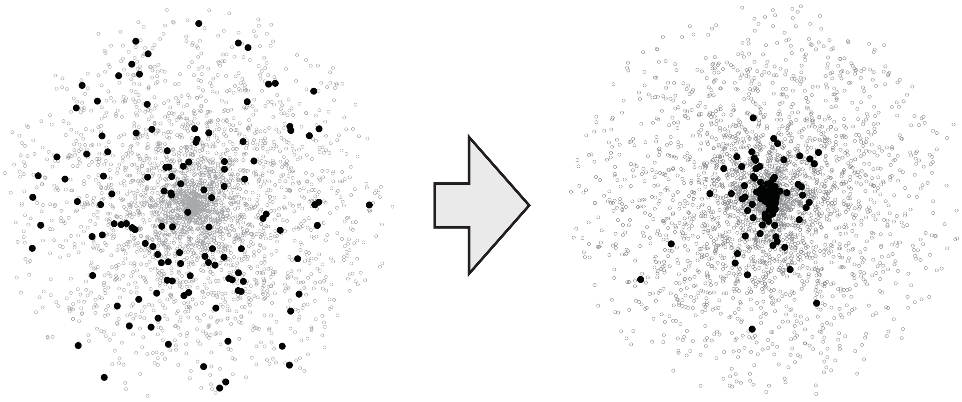

Figure 1.2: *Initially, the distribution of both low- (small grey dots) and high-mass stars (large black dots) is the same. However, after some time, the massive stars are mostly found in the centre, whereas low-mass stars are still distributed as before: this is an example of a mass segregation in a star cluster.*

outskirts. This can be thought of as stars of a given mass moving faster in the core than outside of it. As with other systems, the laws of thermodynamics apply here as well, and therefore there is heat transfer from the core. However, self-gravitating systems, such as stars or star clusters, have a peculiar property that if heat is lost from a system, its temperature increases: the system becomes *hotter*. It can be thought of in the following way: if a satellite loses its energy by friction with the atmosphere, as in the case of low-orbit satellites, it begins to slow down. However, the loss of

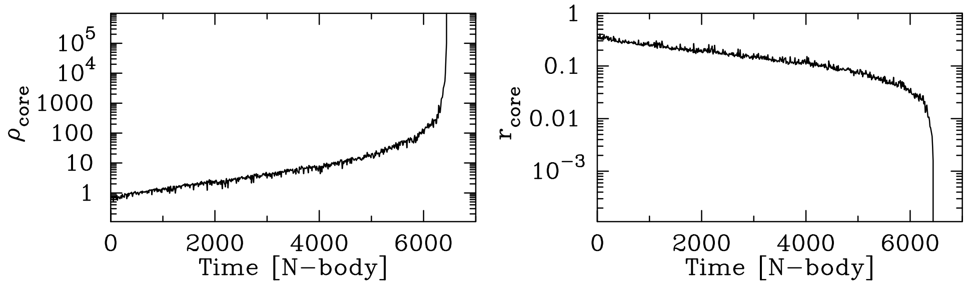

Figure 1.3: *Results from N-body simulations of evolution of a star cluster consisting of* 32768 *equal-mass particles initially distributed according to the Plummer sphere. The left and right panel show time evolution of the core density and radius respectively. The core collapse in this system occurs at* $t \simeq 6440$ *dynamical time units.*

speed results in the decrease of altitude, which means that it starts falling onto Earth; but this actually increases its speed even further, and therefore the speed of the satellite will be increased (becomes hotter). The same applies to the case of a star. When warm (fast moving) stars interact with cold (slow moving) stars, they transfer heat to these cold stars, and instead of slowing down they speed up even further (become hotter) and decay to the core. In this process, the cluster becomes increasingly concentrated: the core becomes smaller and the central density becomes larger. This processes is called *gravothermal instability* (Fig. 1.3). This, in principle, can continue until the core of the cluster becomes indefinitely small and its density reaches infinitely high values, a process which is called *core collapse*. However, in high density environments the occurrence of three-body encounters becomes increasingly probable. The outcome of such an encounter is the formation of a binary (Fig. 1.4). They are basically heat sources which provide enough energy to prevent the core from further collapsing; this is confirmed by both observations and numerical modelling. The further evolution of a star cluster exhibits core oscillations: the periodic collapse and subsequent expansion of the core (Fig. 1.5). This phenomenon is called *gravothermal oscillations*.

The result of both dynamical friction and gravothermal instability is that the core becomes compact enough and sufficiently rich in massive stars, that these stars quickly pair together to form binaries. These massive binaries support the core from further collapse by generating enough heat via interactions with single stars (Fig. 1.6). The result of such interactions is the decrease of the semi-major axis of the binaries. This means that the total energy of the binary decreases, and in order to conserve the total energy of this three-body system, the single star carries away more energy than it brought in. To conserve the total momentum of the system, the binary star

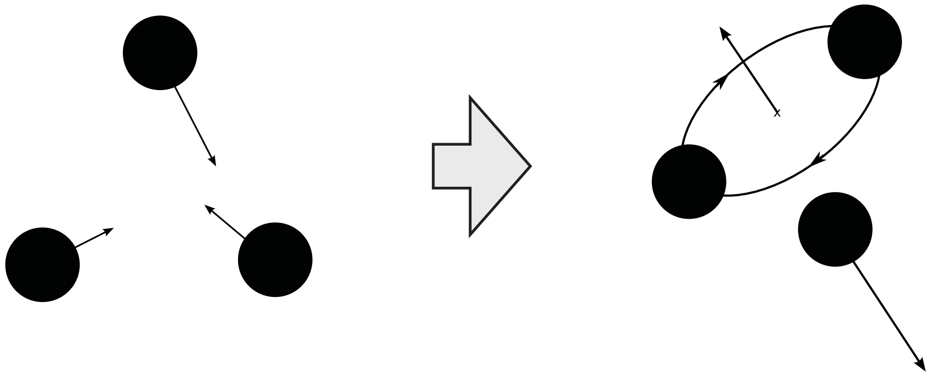

Figure 1.4: *Formation of a binary by a three-body encounter. Initially, three unbound stars come close enough that a complicated three-body encounter takes place. After the interaction is complete, two stars form a binary and a third star escapes to infinity.*

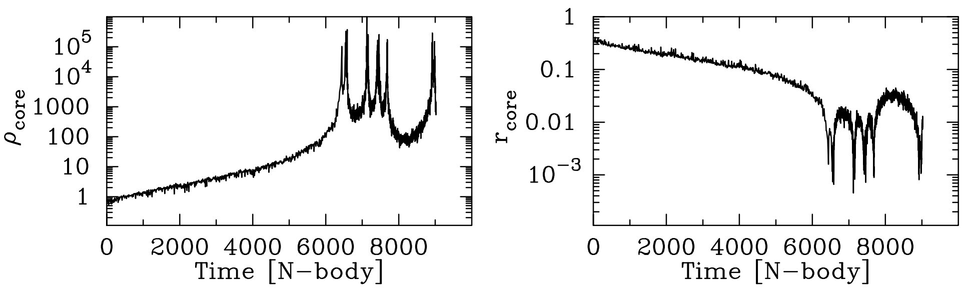

Figure 1.5: *Similar to the Fig. 1.3, except that the evolution is followed beyond core collapse. Gravothermal oscillations are apparent for* $t > 6440$*. The duration of an oscillation is proportional to its amplitude.*

recoils, and on occasion recoil velocity could be high enough that the binary is ejected from the core. This therefore deprives the core from the necessary support against collapse, and the core begins to collapse until another binary is formed. This process can be repeated multiple times, and the core could exhibit sporadic oscillations, which may not necessarily be of gravothermal nature.

Since stars are not point mass objects but have a finite radius, this gives the possibility of stellar merger events, when two stars come so close to each other that a physical contact is unavoidable. Indeed, this may happen when a tight binary interacts with an intruder star. In this case, there is a high probability that two of the three stars during this interaction may come into physical contact and merge. In crowded places, such as central regions of star clusters, collisions appear to be natural events (Hills & Day, 1976), and this has been shown in various numerical simulations (Portegies Zwart et al.,

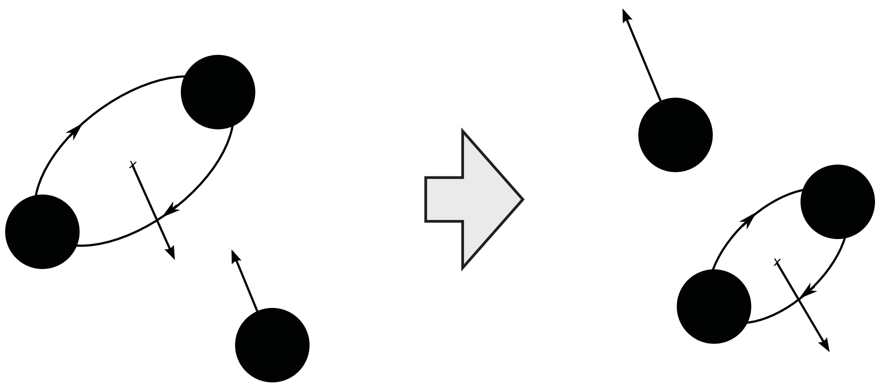

Figure 1.6: *A tight binary interacts with a single star. After the interaction, binary semi-major axis decreases and the excess of the energy is removed by a single star.*

1999; Hurley et al., 2001; Portegies Zwart et al., 2004; Gürkan et al., 2006; Freitag et al., 2006; Gaburov et al., 2008a).

Stellar mergers may provide a formation channel for non-canonical stars, such as blue stragglers that are observed in both open and globular clusters (Hurley et al., 2005), which cannot be explained by the standard theory of star formation (Stahler & Palla, 2005). In young star clusters, stellar mergers might be responsible for the formation of massive stars which are younger than the rest of the cluster stellar population, such as *The Pistol Star* in *The Quintuplet Cluster* (Figer et al., 1998a). Other massive stars, such as *Sher 25* in the massive Galactic cluster *NGC3603*, may have been formed via binary mergers. Along with the single merger events, some star clusters, such as *Arches* close to the Galactic Centre or *R136* in *The Large Magellanic Cloud*, are dense enough that runaway stellar mergers can occur (Portegies Zwart et al., 2004). During such event, many stars merge in succession and this forms a very massive stellar object with a final mass reaching a thousand solar masses. The outcome of such a runaway merger event is still a matter of debate, but this could be a formation channel for an intermediate-mass black hole–a black hole with a mass $m \gtrsim 10^{2-3}\mathrm{M}_\odot$, or an extremely luminous supernova explosion (Portegies Zwart & van den Heuvel, 2007).

1.2 Outline of the thesis

This thesis is the result of an attempt to understand stellar collisions in young star clusters by carrying out dynamic, hydrodynamic and stellar evolution calculations.

Chapter 2 sets the scene, by introducing young star clusters. In particular, we introduce the concept of mass segregation and its influence on the integrated photometric properties of a young star cluster. It is sometimes assumed that in a young mass-segregated star cluster, the core radius strongly depends on the colour of light in which it is observed, for the following reason: massive stars are the first stars to leave the main-sequence and become red, and it is therefore assumed that most of the red light comes from the most massive stars, whereas most of the blue light comes from stars of lower mass. Since most massive stars are expected to be found in the centre of the cluster, it is usually assumed that if the star cluster is observed in red colour, its observed core radius will appear smaller than in blue colour. In this chapter, we use an analytical model to quantify the dependence of the core radius on the colour. We find that the dependence is weak, and the reason is that most of the light for *all* colours comes from stars of similar mass, namely those that are located around turn-off point at a given epoch. But stars with similar masses have a similar spatial distribution, and this therefore results in a weak dependence of core radius on the colour. Therefore, integrated photometric properties are not the best tracer of mass segregation in a young star cluster. Nevertheless, mass segregation still may be detectable by studying the colour of a cluster as a function of the distance to the cluster centre.

In **Chapter 3**, we extend the research further by carrying out a set of N-body simulations of young star clusters with properties similar to the *Arches* cluster situated close to the Galactic centre. This study is motivated by an observational result on the mass function in the central regions of this star cluster. In particular, it was found that the mass function in the central region of the cluster can be approximated as a broken power-law, where the slope becomes shallower for $m > 6\mathrm{M}_{\odot}$, and this was interpreted as due to mass segregation. By carrying out a set of N-body simulations of initially non-segregated star clusters, similar in properties, such as mass and size, to the *Arches* cluster, we are able to reproduce the observations. In addition, we are able to determine from numerical data the time dependence of the slope of the mass function for massive stars, which allows us to constrain the dynamical state of the *Arches* cluster.

Stellar collisions are brought to the scene in **Chapter 4**. In particular, we modelled star clusters similar to the *Arches*, *R136* or *MGG11* clusters, and studied the occurrence of collisions as a function of cluster size. In this work, we were able to identify the main processes which drive collisions, and in addition we have determined initial conditions of collisions, such as the number of participating stars, their mass and their geometry. We found that the time of the first collision is, in general, similar to the time the massive colliding star takes to reach the centre of the cluster from its birth location. Moreover, these collisions occur between a massive binary and a single star, and they could be qualitatively different from the collisions between two single stars, which occur in globular clusters. For massive stars, binary formation by a three-body encounter is much more probable than a collision between two stars. Hence, a massive binary is initially formed, and this binary eventually collides with the third, intruder, star. By detailed studies of the simulation data, we were able to construct a set of initial conditions which can be used for further hydrodynamic studies of such collisions.

Detailed hydrodynamic studies of interactions between binary and single stars is presented in **Chapter 5**. The aim of this chapter is to understand the outcome of an event where a tight massive binary is being strongly perturbed by a massive star. In particular, the number of stars which merge, if any, the final configuration of the system after the collision, mass loss during the collision, and most importantly the comparison against the "sticky sphere" approximation which is commonly used in N-body codes to detect stellar merger events. In the latter approximation stars are hard spheres with a prescribed radius, which is usually equal to the radius of a star of a given mass and age. In the "sticky sphere" approximation, a collision is detected when two spheres touch, or in other words when the separation between centres of these spheres is equal to or less than the sum of their corresponding radii.

While Chapter 5 is focused on the global properties of the outcome of stellar collisions, such as mass loss and geometry, **Chapter 6** studies the internal structure of the collision product. In this case, one has to resort to high resolution simulations, which are computationally demanding. We therefore restricted this study to head-on collisions, which are much faster events than binary-single star mergers, and yet capture the most important processes governing mixing and redistribution of stellar fluid. Since collisions between main-sequence stars occur on time scales which are much shorter than the thermal relaxation time-scale, the fluid elements do not have time to exchange heat; therefore, one can resort to a pure hydrodynamic study of such collisions. Using Archimedes' principle, we found that the fluid redistributes itself such that the fluid with low buoyancy–a quantity which is proportional, but not equal, to entropy–settles, usually, in the centre of the collision product and is surrounded by the fluid with higher buoyancy; in other words, less buoyant fluid is usually below more buoyant fluid. However, if there is a strong chemical composition gradient, it is possible to have a stable configuration of fluid with lower buoyancy on top of the fluid with higher buoyancy. As paradoxical as it may appear on first sight, such a configuration is stabilised by a strong gradient in chemical composition. Since heat exchange was ignored in these calculations, we found that the buoyancy and composition, and therefore temperature, may become multi-valued functions of the radius. This implies that neighbouring fluid elements may have distinctly different values of composition and entropy. Using a semi-analytical method to approximate the structure of a collision product, we found that these multi-valued functions are not an artifact of the simulations, but are a direct consequence of ignoring the microscopic mixing processes. Therefore, we suggest that the microscopic mixing may be an important component in mergers between massive stars, which is currently missing in such type of calculations.

Finally, in **Chapter 7** we study the scenario of forming an intermediate mass black hole (IMBH) by a runaway stellar merger event. Using runaway sequences from the results of N-body simulations, we study the evolution of a runaway collision product. By approximately modelling the structure of the collision product, as presented in Chapter 6, we followed the evolution of such a product between its subsequent collisions with other stars. In N-body simulations, in which the intermediate evolution of the product is usually ignored, the final mass of the product is about a thousand solar masses at the end of the runaway sequences. However, once stellar evolution is taken into account, strong stellar winds appear to drastically modify this result, such that an IMBH is not likely to be formed by means of runaway stellar collisions.