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Stellar collisions in young star clusters

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Summary

The research carried out in this thesis is focused on a systematic study of stellar collisions in young star clusters. Massive stars, which are abundant in young stars clusters, have a profound influence on the dynamical evolution of a star cluster. To simplify the matter, we split the evolution of a cluster in two phases: before and after stellar evolution has a significant impact on cluster dynamics. The evolution of individual stars has little influence on the dynamics of a star cluster in the first three million years of its life. However, after three million years the stellar evolution has a considerable impact on stellar motions due to mass loss in supernova explosions. In this thesis we have mostly focused on star clusters whose age does not exceed three million years, such as Arches cluster in the Galactic Centre or R136 in the Large Magellanic Clouds (LMC).

An important process in the early evolution of a star cluster is mass segregation: stars which are more massive than the average stellar mass migrate to the central region of a star cluster, known as the core of the cluster. As a result of mass segregation, the number of massive stars, and therefore the mean stellar mass, increases in the core and decreases in the outer regions of the cluster. This process continues until a massive binary star is formed in the cluster centre. The further evolution of a star cluster is modified by the presence of a massive binary star. This binary star prevents any further increase of the number of massive stars in the core. Such young clusters are mass segregated, and indeed there is observational evidence of mass segregation in various young star clusters.

It is important to quantify the degree of mass segregation that can be reached via the dynamical evolution alone. This can be compared to the observational data in order to identify the origin of mass segregation in young star clusters: primordial or due to dynamical evolution. An interesting example is the Arches cluster. The present day observational data reveals that the mass function in its core (core mass function) can be fitted with a double power law function: the mass function slope above about six solar masses, which we call pivot mass, is shallower than below. One of the proposed explanations is that Arches' mass function represents the initial cluster mass function (IMF), which has been developed during the cluster formation process. However, it remains unclear why other young star clusters do not have such properties in their IMF.

In this thesis we found that Arches' core mass function is the natural outcome of the dynamical evolution. We studied time and radial dependence of an initially non-segregated cluster with the Salpeter IMF. Even though the core mass function is initially described by a single power law, it eventually deviates from its initial state and develops a break at the pivot mass. We found that the best fit for the simulated mass function is a double, rather than a single, power law. Moreover, the simulation data predict that the pivot mass is equal to twice the mean stellar mass in the cluster. It is important to stress that this result does not require any peculiar mass function and is consistent with the assumption that the Arches was born in non-segregated. Moreover, it predicts that the mean mass of the Arches cluster is about three solar masses–a value which is consistent with the observational data.

A cluster which is non-segregated at birth takes some time to reach the state of mass segregation. This time depends on both the mass and the size of the cluster: the larger and the less massive cluster is, the more time it takes to become mass-segregated. Clusters with age below a certain value cannot reach a segregated state, unless they are born already mass-segregated. The ability to detect mass segregation in young star clusters is an important step in this venture. Observations that rely on the individual star count cannot be applied to the clusters located beyond LMC. For these clusters one has to rely on the integrated properties, such as photometric or spectroscopic.

Integrated photometric properties can, in principle, provide information about mass segregation in young star clusters of co-evolving stars. In segregated clusters, massive stars, which are first to leave main-sequence, are concentrated in the central regions of the cluster, whereas lower mass stars, which are locate farther away, continue their evolution on main-sequence. Main-sequence stars emit most of their light in blue/green colours compared to post-main sequence stars, whose spectra is dominated by red colour. Therefore, size of the observed core of a segregated cluster with the age exceeding three million years should depend on the colour in which the cluster is observed: the core should appear smaller in red colour when compared to blue or green colour. This indeed has been observed in various young star clusters. However, it became clear later that this was caused by different effects, such as differential extinction or variation of point spread functions. After corrections for this effects, size of the observed core was consistent in all colours.

It is therefore desirable to have quantitative estimates on the degree to which mass segregation affects integrated photometric properties. We find in this thesis that most of the light in all colours are emitted by stars in a narrow mass interval concentrated near the turn-off mass at a given epoch. This is the result of a steep dependence of mass-luminosity relation. As a result, stars of similar masses dominate integrated photometric properties for all colours and at all ages. But stars of similar mass have similar spatial distribution, and therefore the differences in observed core radii are small. In our models, which were motived by the Arches' mass function, these differences do not exceed ten percents.

Mass segregation in young star clusters is a necessary condition for stellar collisions. Accumulation of large number of massive stars in a compact region inevitable leads to close interactions between some stars, and some of these interaction are so close that stars may collide and merge. However, the path towards the first collision in young star clusters is rather complicated. The naive assumption that two single stars eventually collide with each other, like in globular cluster, does not hold in young star clusters. Instead, the formation of a massive binary star is a more likely outcome than a collision between two single stars. Collisions are likely to occur between one of the member of a massive binary star, either dynamically formed or of primordial origin, and a single star.

The outcome of a collision between a binary and a single stars can only be studied by means of hydrodynamical simulations. The exact details of the interaction depends on the geometry of the colliding stars, such as binary orientation with respect to the incoming single star, their velocities and masses. Despite the complicate interaction between three stars during a collision event, we found that all three stars participating in the collision are likely to merge. Initially, an intruder stars merges with one of the binary members. The resulting hydrodynamical mess exerts a drag force on the remaining binary system. As a result, the binary separation and eccentricity decreases. Moreover, if the binary separation is small enough, the unstable mass transfer will eventually commence, and binary will merge. In this case, the remaining collision product acquires kick velocity which is caused by the asymmetric mass loss during binary in-spiral. In some cases, this kick velocity is large enough that the collision product can be ejected from the core of a cluster. This therefore predicts an exciting possibility to observe collision products in the outer regions of a star cluster, and the Pistol star, which is located a parsec away from the core, in the Quintuplet cluster is a possible candidate.

In order to study the further evolution of a collision product, it is necessary to understand its structure. This can be obtained by carrying out high-resolution detailed three-dimensional hydrodynamic simulations. However, this is a computationally intensive procedure which can only be used to study individual cases. If one, on the other hand, is interested in modelling large number of merger events, such as in the case of the evolution of a runaway collision product, an approximate and quick modelling is desirable. It turns out that the final distribution of the fluid in the collisions product is governed by a single physical process: the Archimedes' principle. If two stars of same age and with different masses collide together, the fluid from a dense low mass stars occupies the centre of the collision product and is being surrounded by the fluid from less dense high mass star. Nevertheless, some of the fluid from one star is mixed with the fluid of the other star.

In this thesis, we have developed an approximate method which quickly generates the structure of a collision product between two massive stars. In conjunction with stellar evolution methods, this allowed us to make a first attempt to consistently study the evolution of a runaway collision product, which is the result of the merger of a large number of stars within few million years. This process may take place in young dense star cluster. In star cluster simulations, the mass of the runway collision product was exceeding one thousand solar masses. It was therefore hypothesised that such an object can be a progenitor of an intermediate mass black holes.

These simulations, however, ignore mass loss during the collision and during the evolution of the product between merger events. While the former seems to be a plausible assumption since the mass loss in a collision between two main-sequence stars is few percent, the mass loss between merger events, which is caused by strong stellar winds, strongly influences the evolution of the runaway collision product. The mass loss between merger events is strong enough to considerably slow down growth of the product. Moreover, after about two million years since the beginning of the runaway merger event, the collision product becomes a Wolf-Rayet star which have strong stellar winds. As a result, most of the mass gained in merger events for the past two million years is lost just in a half-million year. In this case, the outcome of a runaway merger event is a stellar mass black hole.