When Stars Collide

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Abstract. When two stars collide and merge they form a new star that can stand out against the background population in a star cluster as a blue straggler. In so called collision runaways many stars can merge and may form a very massive star that eventually forms an intermediate mass blackhole. We have performed detailed evolution calculations of merger remnants from collisions between main sequence stars, both for lower mass stars and higher mass stars. These stars can be significantly brighter than ordinary stars of the same mass due to their increased helium abundance. Simplified treatments ignoring this effect give incorrect predictions for the collision product lifetime and evolution in the Hertzsprung-Russell diagram.

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INTRODUCTION

In star clusters stars can experience close encounters with other stars, which in some cases can lead to the collision and merger of two or more stars. This is a possible formation mechanism for blue straggler stars.

Blue stragglers are stars that appear on the extension of the main sequence in the colour-magnitude diagram (CMD) of star clusters (Piotto et al. (2004) and figure 1). In the past, various mechanisms for their formation have been proposed (see e.g. Livio (1993) for a list), but the most commonly accepted explanation is that they are stars that have gained mass long after they were formed, either through mass transfer in a close binary or by merging two stars. Such a merger can in turn be the result of normal binary evolution or of a collision with another star. These mechanisms are thought to operate and produce blue stragglers in different regions in a cluster (Davies et al., 2004). We have studied mergers that result from collisions.

In some cases a sequence of collisions in the centre of a cluster can lead to a runaway where many stars merge together (Portegies Zwart & McMillan, 2002). Such runaways may lead to the formation of very massive stars and ultimately intermediate mass blackholes. We have studied the evolution of the outcome of a single collision.

One of the goals of the MODEST collaboration (Hut et al., 2003) is to study the evolution of stellar mergers by combining stellar evolution, stellar hydrodynamics and stellar dynamics in one software framework. This work is the first result from combining stellar hydrodynamics and stellar evolution in one framework.
STRUCTURE OF COLLISION PRODUCTS

During a collision the potential energy of the two parent stars is released and converted to thermal energy. This means that the collision product initially has a lot of excess thermal energy that needs to be lost by gravitational contraction. In this sense, the collision product resembles a pre-main sequence star.

Unlike pre-main sequence stars, however, collision products are not convective and are not well mixed (Sills et al., 1997). In many simplified descriptions of stellar mergers, the merger remnants are either treated as normal zero-age main sequence stars with the same total mass, or the two stars are assumed to mix homogeneously during the collision (Tout et al., 1997). Neither of these is a very good approximation and the resulting evolution can be very different from a more detailed approach.

In a realistic collision, the collision product is expected to have gained a lot of angular momentum and should spin rapidly. Some of this excess angular momentum needs to be lost before the star can contract to a main sequence position. The mechanism for this is not well understood although magnetic fields are thought to play a role (Sills
FIGURE 2. Composition profile of the merger remnant from a collision between a 1.29 and a 0.59M⊙ star (thick line), compared to that of a normal star with the same core hydrogen content (thin line). Shown profiles are for hydrogen (solid line) and helium (dashed line).

et al., 2005). Rapid rotation can lead to extra mixing and affect the evolution of the stars (Heger et al., 2000; Pinsonneault et al., 1989). Because the mechanism by which angular momentum is lost is not well understood we have not considered the effect of rotation on the results presented here, but we will address this in future work.

We have performed detailed evolution calculations for remnants of collisions involving low mass stars as well as high mass stars. The evolution tracks were calculated with the stellar evolution code originally developed by Eggleton (Eggleton, 1971; Pols et al., 1995), the structure of collision products were calculated in collaboration with E. Gaburov and S. Portegies Zwart using smooth particle hydrodynamics for the more massive stars, and using the parametric code of Lombardi (Lombardi et al., 2002) for the lower mass stars.

COLLISIONS BETWEEN LOW MASS STARS: BLUE STRAGGLERS

As noted, collisions between low mass stars \((M_1 + M_2 \lesssim 2M_\odot)\) are interesting in the context of blue straggler formation in globular clusters and old open clusters.

We have made detailed models of collision products for collisions found in an \(N\)-body
At \( t = 3960 \text{ Myr} \) a collision occurred in the simulation between a 1.29\( M_\odot \) primary and a 0.59\( M_\odot \) secondary star. The primary stars was close to the end of its main sequence. After the collision the collision product had the composition profile shown in figure 2. A large portion of the core from the primary sank to the centre of the collision product, leading to a hydrogen-poor region below \( M = 0.1 M_\odot \). Above this region and below 0.4\( M_\odot \) most of the material comes from the core of the secondary star. Material from the core of the primary lead to an increase in the helium abundance between \( M = 0.4 M_\odot \) and \( M = 0.6 M_\odot \). Material further out has the normal unprocessed composition. The interior is mixed during the early evolution of the collision product by three processes. The sharp increase in the hydrogen abundance at \( M = 0.1 M_\odot \) leads to a peak in the nuclear reaction rate at this location, which leads to the development of a hydrogen burning shell (see figure 3). The hydrogen burning shell drives a convection zone that eventually connects to the convective core, mixing the inner 0.4\( M_\odot \). The region above this is unstable to thermohaline mixing (Kippenhahn et al., 1980; Stancliffe et al., 2007) due to the molecular weight inversion (see figure 3).

By the time the star has reached thermal equilibrium the inner 0.6\( M_\odot \) has been mixed and is helium enhanced compared to the material of the envelope. As a consequence, the
FIGURE 4. Evolution track of a merger remnant from figure 2 compared to that of a normal star born with the same mass (dashed) and a homogeneously mixed version of the collision product (dotted). The collision product starts contracting at point (a) and reaches the main sequence at point (b) after 2Myr and the end of the main sequence at (c) after 0.6Gyr.

mean molecular weight in the star is increased compared to that of a normal star. This affects the luminosity according to the scaling relation (Kippenhahn & Weigert, 1990)

\[ L_{\text{merger}} = L_{\text{ms}} \left( \frac{\mu_{\text{merger}}}{\mu_{\text{ms}}} \right)^4. \]

The star’s temperature is not strongly affected because the volume averaged opacity is not significantly changed. This is because the hydrogen envelope comprises most of the star’s volume. As a result, the collision product is brighter than a normal star of its mass but not as blue as it would have been if the star had been homogeneously mixed (figure 4).

The hydrogen abundance in the core has increased by the mixing, extending the lifetime: the star is rejuvenated.

In addition to the mergers found in the N-body simulation we have computed a number of models to investigate the parameter space \( M_1, M_2 \) and \( t_{\text{collision}} \) for the merger remnants (Glebbeek & Pols, 2007). The results of these calculations are shown as circles in figure 1. The models from our grid nicely fill the blue straggler region in the observed CMD, confirming that merger remnants do look like blue stragglers. The absence of
FIGURE 5. Evolution track of a merger remnant from a 10 and a 7M⊙ star where the primary was at the end of the main sequence. The dashed track is a main sequence star of the same mass, the dotted track is a homogenised model. The points of helium ignition for the collision product and the normal star are indicated by *.

models around the blue and red boundaries of the blue straggler region are an artefact due to the limited range in $M_1 + M_2$ of our grid.

COLLISIONS BETWEEN HIGH MASS STARS

The evolution of remnants from the collision of high mass stars (here loosely taken to mean collisions involving stars that have $M \gtrsim 5M_⊙$) are mainly relevant for the formation of very massive stars ($\sim 100M_⊙$) or so-called merger runaways whereby repeated collisions are thought to lead to the formation of a star with a mass up to $\sim 1000M_⊙$ (Portegies Zwart et al., 2004). Some authors have tried to study the evolution of such massive stars with normal single star models (Belkus et al., 2007; Yungelson, 2006) but this approach neglects the effect of mass increase during the evolution as well as helium enhancement (Glebbeek et al., 2007). Understanding the outcome of the first merger in such a sequence is important for understanding the subsequent mergers with the same object (Gaburov et al., 2007).

The study of mergers of massive stars is more complicated than that of mergers of low mass stars because of the importance of radiation pressure for their stability (Gaburov
et al., 2007). Qualitatively, the evolution of massive collision products is similar to that of lower mass collision products: they settle to a main-sequence like position on a thermal timescale and the inner region is mixed by convection and thermohaline mixing while the envelope is not mixed.

An interesting scenario is the collision between a primary star that has just moved off the main sequence and a lower mass star that is still on the main sequence. The hydrogen exhausted core of the primary will end up in the centre of the collision product, but because there is no hydrogen in the core there is no core nuclear burning until the ignition of helium. In particular, no hydrogen will be mixed into the core by convection: the star does not rejuvenate. This means that the collision product will contract to a position at the beginning of the Hertzsprung-gap rather than the main sequence, but with the lower core mass appropriate for a lower mass star. The remnant of the collision between a 10 and a $7M_\odot$ solar mass star shown in figure 5 contracts on a timescale of $3.6 \times 10^4$ yr, after which the star starts to cross the Hertzsprung-gap. Due to its lower core mass, the star begins core helium burning (CHeB) while it is bluer than a normal star of the same mass and metallicity. Like a more massive star or a star of lower metallicity the collision product spends about one third of its CHeB phase in the blue part of the colour magnitude diagram. It takes $\sim 1$ Myr to cross from the beginning of the Hertzsprung-gap to the red branch while an ordinary star of the same mass takes only $\sim 4 \times 10^{-2}$ Myr.

A major complication in the study of massive collision products is the uncertainty in the mass loss rates for the remnants of these stars as well as the interplay between mass loss and rotation. Especially after multiple collisions the collision products can become very bright, close to their Eddington luminosity

$$L_{\text{edd}} = \frac{4\pi GcM}{\kappa} \tag{2}$$

Stars that become this bright have a high mass loss rate or eject mass in large outbursts. A better understanding of the mass loss rates for this type of object is needed to predict the outcome of runaway mergers (Glebbeek et al., 2007).

**CONCLUSIONS**

Stellar collisions are a means of making stars that appear in unusual locations in the colour magnitude diagram, such as blue stragglers. Remnants from high mass stars that merge after the end of core hydrogen burning can become much brighter while crossing the Hertzsprung-gap and stay there much longer.

Approximating mergers with ordinary stellar models or fully mixed models can give significantly different results compared to proper detailed models.

**UNANSWERED QUESTIONS**

The main uncertainty in the evolution of stellar collision products is how they lose their excess angular momentum and, consequently, the importance of chemical mixing due to rotational instabilities.
It is known that collision products need to lose angular momentum before they can settle into hydrostatic equilibrium. Magnetic fields might play an important role in this angular momentum loss, but nothing is currently known about the configuration of the magnetic field after the merger.

Very massive collision products can reach luminosities close to their Eddington limits, particularly for runaway mergers where many stars collide. The mass loss rates become very uncertain at this point. This introduces a large uncertainty in the evolution of very massive stars and the type and mass of their remnants since these are mainly determined by the mass loss rate.

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