# The evolution of stellar collision remnants

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## 2. Summary

We intend to develop a consistent numerical framework for modeling stellar collisions, and to further evolve these collision products with a robust stellar evolution code. Collisions between stars are common in dense star clusters, where they can result in blue stragglers and very massive stars. These merger products are important tracers of the dynamical processes inside dense clusters.

We request financial support for two PhD students: one will work on the hydrodynamics of stellar collisions and the other on the stellar evolution of collision remnants. The work will result in two routines that will be implemented in existing $N$-body solvers to study the dynamical evolution of dense star clusters.

## 3. Classification

Astronomy

*Sub-classification:* Hydrodynamics – Stellar dynamics – Stars: evolution – Globular clusters – Open clusters and associations – Methods: N-body simulations – Methods: numerical

## 4. Composition of the research team

1. Dr. Onno R. Pols (P-I)
   Astronomical Institute, Utrecht University
   *expertise:* stellar evolution
2. Dr. Simon F. Portegies Zwart (Co-I)
   Astronomical Institute and Computational Science Section, University of Amsterdam
   *expertise:* stellar dynamics
3. Dr. James C. Lombardi
   Dept. of Physics and Astronomy, Vassar College, Poughkeepsie, New York, USA
   *expertise:* stellar hydrodynamics
4. Dr. Alison Sills
   McMaster University, Hamilton, Ontario, Canada
   *expertise:* stellar evolution and hydrodynamics
5. Prof. Dr. Norbert Langer
   Astronomical Institute, Utrecht University
   *expertise:* stellar evolution and rotation
6. Prof. Dr. Frank W. M. Verbunt (promotor)
   Astronomical Institute, Utrecht University
   *expertise:* open and globular clusters
7. Prof. Dr. Edward P. J. van den Heuvel (promotor)
   Astronomical Institute, University of Amsterdam
   *expertise:* compact objects
8. N.N. (Ph.D. student to be appointed)
   Astronomical Institute, Utrecht University

9. N.N. (Ph.D. student to be appointed)
   Astronomical Institute, University of Amsterdam

## 5. Research school

Nederlandse Onderzoeksschool Voor Astronomie (NOVA)

## 6. Description of the proposed research

### The importance of stellar collisions and mergers

In dense stellar environments, such as globular clusters and the dense cores of young clusters, close encounters between stars are very frequent and many stars collide and merge. This has been demonstrated in several $N$-body simulations (e.g. Portegies Zwart et al. 1999; Hurley et al. 2001). Close stellar encounters can give rise to a variety of exotic objects such as X-ray binaries, millisecond pulsars, cataclysmic variables and contact binaries. Furthermore, stellar mergers can produce non-canonical stars like blue stragglers and, in very young clusters, stars of mass $> 100\,\mathrm{M}_\odot$. Observatories like *HST* and *Chandra* are now providing a wealth of observational data of such objects in the heart of the densest clusters.

Blue stragglers (BS) are stars located along the extension of the main sequence, above and blueward of the turnoff point in the cluster color-magnitude diagram (CMD). They are very common in old open clusters like M67, as well as in globular clusters. Spectroscopic observations confirm that blue stragglers are indeed more massive than turnoff stars (Shara et al. 1997) and in some cases even more massive than *twice* the turnoff mass (the so-called super-BS). A well-known super-BS is F81 in M67, which has a mass of $\approx 3\,\mathrm{M}_\odot$ (Leonard 1996) compared to the turnoff mass of $1.3\,\mathrm{M}_\odot$, and they have also been identified in the cores of globular clusters like NGC 6397 (Sepinsky et al. 2000). Evidently, more than two stars must have been involved in the formation of a super-BS. This clearly points in the direction of dynamically induced, multiple collisions as the origin.

Except in the cores of the densest clusters (Hills & Day 1976) and in galactic nuclei (Freitag 2000), direct collisions between single stars are rare. However, indirect collisions by means of resonant interactions involving binary stars are frequent even in lower-density clusters (Leonard 1989). The rate at which stars collide and merge depends directly on cluster properties like density, velocity dispersion, masses and binary fraction. Mergers themselves change these properties, and thereby affect the overall dynamics of the cluster. This results in an intricate interplay between individual stellar interactions and the cluster evolution as a whole. Since merger products stand out observationally, they can serve as important diagnostics of the dynamical processes taking place inside the cluster.

In the densest globular clusters red giants are strongly depleted relative to horizontal branch stars. This is impossible to understand purely from stellar evolution, but the dynamical history of the cluster provides an explanation via collisions involving giants in close binaries (Beer & Davies, 2003). A related problem is the morphology of the vertical horizontal branch in old globular clusters (Sandage 1990), which is thought to be the result of strong dynamical activity.

Apart from blue stragglers, we expect a population of their post-main sequence remnants. These may be observable as “yellow” stragglers, as in M67 (Landsman et al. 1997), or are hidden in the giant branch. They may be identifiable by abnormal surface abundances or rapid rotation, if not by their unusual position in a cluster CMD. One of the brightest giants in the old open cluster NGC 188 is a rapidly rotating FK Comae-type star and a bright X-ray source (Belloni et al. 1998) Other objects which may have had an origin in stellar mergers are the super-massive Pistol star (Figer et al. 1998), the peculiar binaries $\iota$ Orionis (Bagnuolo et al. 2001) and OW Gem (Griffin & Duquennoy 1993) and the extraordinary supernova 1987A (Podsiadlowski et al. 1990)

In order to interpret the observations we need to understand the details of the merger process, in particular: what kind of remnants are produced, and how do they evolve once they are formed. Understanding their evolution is essential for two reasons. Firstly, the merging process itself takes place on a very short, dynamical timescale, so we can only observe the evolved merger remnants. Secondly, $N$-body simulations have shown that merger remnants, which are among the most massive objects in a cluster, are more likely to undergo further collisions than other stars. This can lead to runaway mergers.

Hurley et al. (2001) modeled the blue straggler population of an old open cluster like M67. They found that about half of the blue stragglers result from normal binary evolution (conservative mass transfer, or the merger of a close primordial binary). The other half formed as a result of single-binary and binary-binary interactions, causing two of the participating stars to collide. An important result was that many blue stragglers (about 10 per cent) formed with more than twice the turn-off mass of the cluster, as a result of multiple collisions. In one case, a star with *six* times the turn-off mass was formed, as a result of four successive collisions, two of these with other blue stragglers.

Portegies Zwart et al. (1999) simulated young, dense star clusters like R136, the central star cluster in the 30 Doradus region of the LMC. They found stellar collision are very common in the center of this cluster. The most remarkable result was that the same star participated in several collisions in close succession, leading to a runaway merger. In one of their models the most massive star experienced about a dozen collisions with other, lower mass stars until it reached a total mass of more than $180\,\mathrm{M}_\odot$. This super-massive blue straggler finally collapsed into a black hole.

Many unusually bright X-ray point sources have been discovered using *Chandra* in the irregular galaxy M82 (Matsumoto et al. 2001) , the “Antennae” system (NGC 4038/4039; Fabbiano et al. 2001) and other galaxies. The brightest X-ray source in M82 has a luminosity of $9 \times 10^{40} \mathrm{erg\,s^{-1}}$, which corresponds to the Eddington luminosity of a $\sim 600\,\mathrm{M}_\odot$ compact object. The variability of the source (Matsumoto et al. 2001) and its high luminosity indicate that it may be a single intermediate-mass black hole (IMBH) with a mass of at least $600\,\mathrm{M}_\odot$. An optical follow-up in the infrared revealed a young ($\lesssim 10$ Myr) star cluster with an estimated mass of a few $10^6\,\mathrm{M}_\odot$ at a position consistent with the X-ray location of the IMBH (Matsumoto et al. 2001).

A possible explanation for the formation of an IMBH was recently proposed by Portegies Zwart & McMillan (2002). They found that star clusters with initial half-mass relaxation times $\lesssim 20$ Myr are dominated by stellar collisions, the first collisions occurring at or near the point of core collapse. The majority of collisions occur with the same star, resulting in the runaway growth of a supermassive object. This object can grow up to $\sim 0.1\%$ of the mass of the entire star cluster and could manifest itself as an intermediate-mass black hole (IMBH).

There is now a general consensus that collisions, including multiple collisions, are common in star clusters. With the seminal work of Sills et al. (1997, 2001) it became clear that a collision between two main-sequence stars can indeed lead to a blue straggler, even though the remnants generally have too much angular momentum and it is not yet clear how the excess angular momentum is lost. What happens upon subsequent collisions is much less clear, and whether these indeed lead to the formation of super-blue stragglers has not been explored with detailed models. There are several steps in this process that require a better understanding of the underlying physics. At the moment the only clear concept in the formation of massive stars via a collisional runaway is that the stars will be rotating very rapidly.

Massive stars live rather short and at the end of their nuclear burning lifetime they collapse to black holes. The details of how to get from a massive star to a black hole are far from understood (Fryer & Warren 2002), especially when the progenitor is rapidly rotating. On the other hand there are indications from observed gamma-ray bursts (GRB) that massive rapidly rotating stars do collapse to black holes. Price et al (2002) conclude from the multicolour excess in the afterglow, the near infrared and radio observation of GRB 011121 that its progenitor was most likely a rapidly rotating $\gtrsim 150\,\mathrm{M}_\odot$ star. The GRB and supernova could have occurred in a dense star cluster, in which case the high mass star may be the result of a collision runaway (GRB 011121 occurred at $z = 0.36$, too distant to identify a star cluster).

Our current lack of detailed understanding of stellar collision remnants and their evolution is one of the main hurdles toward interpreting the observations mentioned above, and toward understanding the evolution of star clusters as a whole. This was the consensus at two recent workshops of the MODEST collaboration[1]. The aim of this project is to improve this situation by developing a numerical framework for modeling stellar collisions and the evolution of collision remnants.

### How do stellar merger remnants evolve?

In all $N$-body simulations of star clusters done so far, the modeling of merging stars (either through binary evolution processes or as a result of collisions) was very crude. It is assumed that when two stars hit, they simply stick together. After merging, the remnant is assumed to behave and evolve like a normal single star of the combined mass, with a correction to the remaining lifetime for the effect of already burnt hydrogen. The lifetime (and thereby the observable number of such objects) and position in the CMD strongly depend on this assumption, severely hampering a comparison with observations.

The reason for the crudeness of current models is that virtually no detailed results are available of how merged stars *do* behave and evolve. Only for a limited number of mass combinations, evolution states and impact parameters have detailed hydrodynamical computations of stellar collisions been attempted. Stellar evolution calculations of collision remnants are even sparser. However, the few existing calculations have led to important insights.

Hydrodynamical simulations of stellar collisions between main-sequence stars have been performed by Benz & Hills (1987) and more recently by Lombardi et al. (1995, 1996) and Sills et al. (2001). These calculations have shown that the structure and chemical composition of a collision product can be very different from that of ordinary single stars. The structure and composition profile depend on the masses and evolutionary state of the original stars, as well as on the impact parameter and relative velocity. Since these can vary enormously in a star cluster, we expect an enormous variety of merged objects.

These simulations have also demonstrated that the collision remnants are strongly out of thermal equilibrium and, except in the very rare cases of head-on collisions, are rotating very rapidly. The amount of angular momentum is so large that the star cannot contract to thermal equilibrium without shedding a large fraction of its angular momentum. The star must do so without losing a correspondingly large fraction of its mass in order to become identifiable as a blue straggler. The mechanism by which angular momentum is drained is not yet understood; possibly it is due to magnetic locking of the star to a disk (Königl 1991) formed after some mass is lost at the equator.

The evolution of stellar merger remnants has hardly been studied. Only a few detailed evolution calculations have been performed (Sills et al. 1997, 2001) for collisions involving low-mass main-sequence stars. What these calculations have shown is that the further evolution can be quite different from that of a canonical star of the same mass. This is partly the result of the different structure and chemical composition of the star, and partly the result of its rapid rotation. Such rapid rotation can cause significant extra mixing in a merger remnant, shifting its position in the CMD and prolonging its lifetime. Because the mixing is not complete, however, the evolution cannot simply be approximated by that of a homogeneous star. The calculations by Sills et al. demonstrate that the evolution of a merger remnant is sensitive not just to the total mass, but also to the evolution states of the original stars before collision, as well as to the collision impact parameter.

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[1] MODEST is a loose collaboration of people interested in MOdeling DEnse STellar systems, particularly those interested in developing a framework in which all relevant physics (stellar dynamics, stellar evolution and hydrodynamics and the interplay between the three) can be modeled together in one simulation. See the two review articles by Hut et al. (2003) and Sills at al. (2003) or visit the MODEST website at `http://www.manybody.org/modest.html`. The second MODEST workshop was held in December 2002 in Amsterdam with support from NWO and NOVA.

What we need in order to make progress in understanding the impact of stellar mergers on the evolution of dense stellar systems, is a reliable model for the evolution of merged stars for arbitrary masses, evolution states and collision impact parameters. In other words, we need an algorithm that (1) computes the structure and chemical composition of an arbitrary merger remnant, and (2) evolves such objects further to the end of their nuclear and thermal evolution. Our ultimate goal is to be able to evolve an entire star cluster, including stellar and binary evolution, with realistic modeling of stellar mergers and (multiple) collisions. Given the enormous variety of collision parameters that is expected, we need to perform both calculations (1) and (2) on the fly, simultaneously with the stellar dynamics. We intend to address both problems in concert by applying for two PhD students.

A first step toward achieving (1) has already been made on the basis of hydrodynamical calculations for collisions between low-mass main-sequence stars (Lombardi et al. 1995, 1996, Sills et al. 2001). For the relatively low-velocity collisions expected in open and globular clusters, the structure and chemical composition of a merger remnant are determined by "entropy sorting": the highest entropy material of both stars sinks to the center, while low-entropy gas ends up in the outer layers. This has allowed the construction of a simplified algorithm that yields the structure and composition of a merger product within a fraction of the time it takes to do a full-scale hydrodynamical simulation (Lombardi et al. 2002). This entropy-sorting algorithm is efficient and can easily be implemented into stellar dynamics codes (e.g. an *N*-body code or a Monte-Carlo algorithm).

Such hydrodynamical calculations have *not* been performed in a systematic way for collisions involving other types of star: either massive main-sequence stars, or more evolved stars (sub-giants, giants, compact stars). Although giants are less abundant than main-sequence stars, their cross-section is proportionally larger and about 20 per cent of the collisions in an open star cluster are expected to occur involving giants (Portegies Zwart et al. 1997). In order to evolve an entire star cluster taking into account the details of (multiple) collisions, we must understand the merger remnants of such collisions as well. We aim to achieve this by performing SPH calculations of collisions involving massive main-sequence stars, as well as evolved stars, allowing us to generalize and extend the entropy-sorting algorithm. This will be the research topic of the first PhD student. The evolution of merger remnants has to be calculated using a detailed stellar evolution code, given the enormous variety of remnant structures that we expect. This will be the research topic of the second PhD student.

## Research method

The project requires the development of two codes, together with interfaces for implementation into a stellar dynamics code. These interfaces should be general, so that the codes can be used together with any dynamical code (be it an *N*-body code, a Monte-Carlo code, or some hybrid). This is the aim of the MODEST collaboration, to which we wish to adhere closely. For our specific purposes, we will implement the codes into the `starlab`[2] software environment (Portegies Zwart et al. 1998), which encompasses a high-precision direct *N*-body integrator.

*Hydrodynamics of stellar mergers* We need to know the structure and composition profile of the merged object before we can evolve it further. Concretely, what is required by the stellar evolution code are the profiles of entropy and of the mass fractions of the relevant isotopes, as a function of mass coordinate. These profiles can be provided by hydrodynamics calculations of stellar mergers, e.g. smooth particle hydrodynamics (SPH; Lombardi et al. 1996). However, each of these calculations is very time-consuming. A very useful tool has been developed by Lombardi et al. (2002) which utilizes the fact that in the SPH models the different parts of the colliding star are sorted by specific entropy. To this is added the relatively small contribution of shock heating. This determines both the entropy and composition profiles

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[2] see `http://www.manybody.org/starlab.html`

of the merger product. This entropy-sorting algorithm, also called Make-Me-A-Star (`MMAS`)[3], is much faster and more efficient than full-scale hydrodynamics calculations, at little cost of accuracy.

So far this `MMAS` algorithm is only available for low-mass main sequence stars up to $0.8\,M_\odot$. This is basically due to the lack of a full-scale hydrodynamics calculations for higher-mass stars, as well as for more evolved stars, against which the `MMAS` algorithm has to be tested and calibrated. For this reason we ask for one PhD position, whose task will be to perform SPH calculations, for a large variety of stellar masses, evolution states and impact parameters. These calculations will be the basis for an extended `MMAS` algorithm, which will be calibrated against the results of the detailed models. We will use the SPH code developed by Dr. J. Lombardi, who is the world expert on these type of calculations and who will be strongly involved in this part of the project. We have a very good candidate for this position, a former undergraduate student of Dr. Lombardi. He already has experience in using the SPH code for this kind of calculations.

The same SPH code will be used to study the result of multiple collisions. After having calibrated `MMAS` for a larger parameter space we intend to continue the calibration process for multiple collisions. The ultimate goal of this part of the project is to construct a numerical routine which takes two arbitrary stars as input and produces a reliable merger remnant of these two stars. The output should be in such a form that a stellar evolution code can continue the evolution of the star after the multiple collision.

*Evolution of merger products* We require a stellar evolution code that can evolve any product of a stellar merger or collision. Because we want to implement the code into an $N$-body environment, it has to be very robust. The code should be able to run through all stellar evolution phases without human intervention. Furthermore it should be able to handle any input model, regardless of whether it is in thermal equilibrium or not.

Currently available codes are inadequate because they cannot handle starting models that are out of thermal equilibrium, and they are not robust enough. Therefore we ask for a second PhD position, who will develop the required code by modifying an existing stellar evolution code and apply it to the evolution of merger remnants. In Utrecht, there are currently two stellar evolution experts (Dr. Pols and Prof. Langer) and two independent stellar evolution codes. Therefore we feel that Utrecht is the ideal place to conduct this research. Dr. A. Sills, who is the leading expert on the evolution of merger remnants, has also offered to be available for consultation.

As the starting point we propose to use the Eggleton stellar evolution code (Eggleton 1971, 1972), which has been updated, modified, tested and used extensively by the P-I, Onno Pols (Pols et al. 1995, 1998). This code is already quite robust under 'normal' circumstances, i.e. when evolving single stars, and even certain types of binary star. It does break down at certain predictable points, e.g. at the core helium flash in low-mass stars, and the onset of thermal pulses on the asymptotic giant branch (AGB). Breakdown at the He flash can quite easily be circumvented by constructing a zero-age horizontal branch model with the same chemical composition. We intend to model the AGB phase using a rapid synthetic evolution algorithm rather than with a full-scale evolution code, because the latter will be too time-consuming even if it can be made robust. Such a synthetic algorithm is currently being developed in collaboration with Dr. C. Tout and co-workers at the Institute of Astronomy in Cambridge (Izzard et al. 2003). Part of the project will consist of recognizing such anticipated breakdowns, and automating the transitions so that the evolution code can run without human intervention.

For the non-canonical stars that we need to model, several additional issues need to be addressed. First, a modification is required so that the code can start with an input model that is not in thermal equilibrium (TE). At the moment this is not possible, but it can be achieved by a procedure of forcing a smooth transition in small steps between an existing TE model and the aimed-for non-TE model.

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[3] see `http://faculty.vassar.edu/lombardi/mmas/`

Second, the code should be able to model the effect of rapid rotation. As discussed above, the merger remnant generally has to lose a large amount of angular momentum before it can relax to thermal equilibrium. Failing a detailed physical model, we will initially adopt an ad-hoc procedure to remove angular momentum based on the disk-locking hypothesis. The effect of rapid rotation, in particular rotationally induced mixing, on the evolution has been shown to be important (Sills et al. 2001) and should therefore be included. The evolution code of N. Langer, also available in Utrecht, already includes these effects (Heger et al. 2000). This allows us to combine techniques from that code into our evolution code, as well as to test our code against the more sophisticated (but time-consuming) Langer code.

Finally, the non-canonical stellar models we expect to result from mergers may cause the code to break down at less predictable points in the evolution than mentioned above. At this stage, very little can be said about what we may expect in this regard.

*Star cluster simulations* The above efforts will result in two codes: an extended `MMAS` routine for determining the structure of merger products, and an `EVOL` routine to compute their further evolution. Both will be implemented into `starlab`. The routines should be easily portable to other $N$-body solvers, such as the Barnes & Hut (1986) tree algorithm, a Monte-Carlo $N$-body integrator (Giersz & Heggie 1994) or a Fokker-Planck code (Takahashi 1997)

If time allows, the students will perform $N$-body simulations which include their newly developed techniques. Portegies Zwart & McMillan (2002) demonstrated that in clusters of single stars, stellar collision start to dominate the evolution if the initial relaxation time is $\lesssim 20\,\mathrm{Myr}$. An independent collision channel is added if the models start with primordial binaries. Star clusters with a few thousand stars are large enough to guarantee many interesting collisions to occur. These $N$-body simulations can be easily performed on a PC. The main goal of these simulation will be the characterization of the collision products in open star clusters, such as Hyades and Praesepe. In this context we note that a wealth of observational data on open clusters is fast becoming available, for instance from the WIYN survey (e.g. Sarajedini et al. 1999), with which we can compare our results.

### Relation to running research programs

The research proposed in this project fits in very well with the work on stellar and binary evolution already conducted in Utrecht by Pols and Langer. It also closely relates to the work of Verbunt, who has a long-standing expertise in optical and X-ray observations of dense open and globular clusters, including blue stragglers (e.g. van den Berg et al. 2001). His input will be invaluable when it comes to an observational interpretation of our work.

The proposed research fills in an important gap in the research currently conducted in Amsterdam. The team of Portegies Zwart works on the evolution of dense star clusters and on the formation of intermediate mass black holes. Our lack of understanding stellar collisions and how collision products continue their evolution has become a major uncertainty in the dynamical models. The consequences can be far reaching as our theoretical knowledge hinges in part on these large numerical simulations.

### Relation to research in other places

We intend to collaborate closely with Dr. J. Lombardi (Vassar College, USA). He is an expert on the hydrodynamics of stellar collisions, and our work builds on his earlier work on the `MMAS` algorithm. Also the work of Dr. M. Freitag (ARI, Heidelberg, Germany) and Dr. F. Rasio (Northwestern University, USA) are of importance for the proposed project. Freitag has worked on collisions near the Galactic center and on possible formation scenarios for intermediate mass and supermassive black holes, while Rasio's group mainly concentrates on globular clusters. At this moment, the only other person involved in evolutionary calculations of collision products is Dr. A. Sills (McMaster University, Canada), who is the world leading expert on this subject. She will be closely collaborating with us on this topic.

This work will be conducted in close collaboration with the `starlab` team, which includes Prof. P. Hut (IAS, USA), Prof. J. Makino (Tokyo, Japan), Prof. S. McMillan (Drexel, USA) and Dr. S. Portegies Zwart). Our work on modeling dense star clusters is closely related to that of Dr. J. Hurley and M. Shara (AMNH, New York) and Dr. S. Aarseth (Cambridge, UK). Though independent from the `starlab` team, both groups collaborate loosely in the MODEST context. We expect to exchange results and, when functional, our merger-remnant evolution algorithms to allow a validation of our results using independently developed software.

## 7. Work programme

Ideally both PhD students would start at the same semester. In their first year both will made themselves familiar with the dynamical environment in which stellar collisions are important, which are: 1) the evolution of close binaries and 2) the dynamical evolution of dense star clusters.

**Stellar collision student: University of Amsterdam** In the first year the student starts specializing in the hydrodynamics of stellar collisions and adjust Dr. J. Lombardi's SPH code. This will be done in collaboration with Lombardi. The students will in that period visit Vassar college for an extended period. In the second year SPH calculations of a range of initial stellar masses, impact parameters and evolutionary stages will be performed and the `MMAS` algorithm tested and calibrated. The stellar evolution student (see below) can then already start using these as input for the models calculations. In the third year the student will extend the `MMAS` algorithm and perform SPH models for multiple collisions. In the fourth year the work will be rounded off and the thesis is written.

**Stellar evolution student: Utrecht University** In the first year the student will familiarize him/herself with the existing stellar evolution code, and begin modifying the code to allow non-TE starting models (as supplied by the already existing `MMAS` routine). Continuing into the second year, further modifications will be made to automate the circumvention of anticipated breakdowns at the helium flash and the transition to a synthetic evolution algorithm at the start of the AGB. By the end of the second year, we aim to have a reasonably robust stellar evolution code that can handle stellar merger products supplied by the extended `MMAS` routine (see above), as yet without rotation. The results of evolution calculations for merger products can serve as input for multiple collision SPH calculations for the Amsterdam student. In the third year rotation will be implemented in the stellar evolution code, and any unforeseen breakdown situations will be dealt with. The fourth year is for finishing the work and writing the thesis.

Dr. Onno Pols will directly supervise the Utrecht student, while Dr. Portegies Zwart will supervise the Amsterdam student. They are responsible for the respective students' research training and education. Profs. Langer, Verbunt and van den Heuvel are expected to play a minor role in the daily supervision, but are available for frequent consultation. Both the stellar evolution group in Utrecht (including Pols and Langer) and the stellar dynamics group in Amsterdam (including Portegies Zwart) are very interactive and hold weekly group meetings, so that there is ample opportunity for feedback with other group members. We also plan to have regular joint meetings of the two groups, alternatively in Utrecht and Amsterdam.

## 8. Expected use of instrumentation

Detailed stellar evolution and hydrodynamical calculations are not particularly computationally intensive; most of the work can be conducted on a fast PC. In the case the more computer power is required we will turn to the University of Amsterdam Beowulf cluster and eventually to TERAS at SARA (see `http://www.sara.nl`).

## 9. Literature

### Five main publications of the research team

Hurley J.R., Tout C.A., Aarseth S.J. & Pols O.R., “Direct *N*-body modeling of stellar populations: blue stragglers in M67”, 2001, MNRAS, 323, 630

Lombardi, J. C., Rasio, F. A., Shapiro, S. L., “Collisions of main-sequence stars and the formation of blue stragglers in globular clusters”, 1996, ApJ, 468, 797

Pols, O. R., Tout, C. A., Eggleton, P. P., Han, Z.. “Approximate input physics for stellar modeling”, 1995, MNRAS, 274, 964

Portegies Zwart, S. F., Makino, J., McMillan, S. L. W., Hut, P., “Star cluster ecology. III. Runaway collisions in young compact star clusters”, 1999, A&A 348, 117

Portegies Zwart, S. F., McMillan, S. L. W., “The Runaway Growth of Intermediate-Mass Black Holes in Dense Star Clusters”, 2002, ApJ 576, 899

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## 10. Requested budget

| item | cost (€) |
|---|---:|
| OiO 1 | 135.762 |
| Benchfee | 4.538 |
| OiO 2 | 135.762 |
| Benchfee | 4.538 |
| Computers | 6.000 |
| Work visit (2 × 3 months, Vassar, USA) | 10.000 |
| Work visit (2 × 3 months, McMaster, Canada) | 10.000 |
| Total cost estimate: | 306.600 |

**Computers** Even though the calculations to be performed do not require immediate supercomputer access, a fast PC will be required for each student. We estimate the cost of a PC with the fastest available processor at the time of purchase, including sufficient memory and disk storage, at € 3.000 each.

**Work visits** We anticipate two 3-month visits for each of the students to either Vassar College (Dr. J. Lombardi) or to McMaster University (Dr. A. Sills). At these locations the students will familiarize themselves with the local expertise on hydrodynamical simulations and stellar evolution of collision remnants, and the inteface between the two. The cost of each visit, including air travel and local expenses for 3 months, is estimated at € 5.000.

We also consider conference participation essential for each of the students, about once a year. In the context of the MODEST collaboration, 2 or 3-day workshops are organized about twice each year. These are very important platforms to present and discuss our results, and we anticipate that each workshop will be attended by one of the students in turn. The € 4.538 benchfee should be reserved for this.