Mergers of massive stars and their impact on the Universe

This project aims to understand and quantify how interaction and mergers between massive stars affect the role they play as cosmic engines.

Massive stars shape the Universe; with their high luminosities, strong stellar winds and violent deaths, they can be considered as the main <u>cosmic engines</u> that transformed the pristine Universe, left after the Big Bang, to the modern Universe, in which we live today.

<u>Most massive stars have a nearby companion</u> [1,2], with which they can interact and even merge [3,4]. Mergers –just like any massive star – play their role as cosmic engines, polluting their surroundings in which new stars and their planets are being formed. However, the mass ejected by mergers will substantially different from the ejecta of single stars, by amount and composition. For example, the high rotation rates expected for mergers trigger extra mass loss and mixing processes in the star that bring chemical elements to the surface, which are normally locked inside the stellar core. Being bluer and brighter than single stars of comparable mass, they may efficiently ionize their surroundings and they make stellar population appear younger than they really are. They may end their life as one of the most luminous explosions in the Universe: gamma ray bursts [5,6], such as the one observed in April 2009, which originated from a time when the Universe was in its childhood, at five percent of its current age [7,8], the earliest and most distant object observed.

About <u>1 out of every 10 stars is expected to merge</u> with a companion star [9, and 3,4]. Although this number is highly uncertain, it likely to be higher, rather than lower, among massive stars, given the high fraction occurring in close binary systems. Moreover, among the brightest objects in a young stellar population, the fraction mergers may be very significant, because they are typically brighter and form after single stars of comparable mass have died. We need to understand the effects of interactions and mergers before we can interpret the data of young stellar populations (Figure 1). This is the aim of this project, which will address the following main questions:

I. How common are mergers of massive stars and what are their properties?
II. How do mergers affect the role of massive stars as cosmic engines?
III. Do mergers result in the most luminous explosions in the Universe?

Due to the complexity of the interaction processes and the computationally challenging nature of the computations, binarity is often ignored in studies of massive stars and stellar populations. However, <u>computational tools suitable to conduct this project are available and I have ample experience with these tools</u>.

<u>Theoretical modeling has not kept pace</u> with the enormous <u>observational progress</u> of the past few years. *Spitzer* revealed young star clusters, rich in massive stars that were previously hidden in the dust that surrounds them [10]. The *Hubble Space Telescope* enabled us to resolve young stellar populations even beyond the local group of galaxies. *Herschell* will allow us to probe star forming regions in the nearby and the distant universe. Only if we <u>develop our theoretical understanding needed to interpret the wealth of observational data</u> available, we can achieve <u>a major breakthrough</u> in our understanding of massive stars and how they contributed to the transformation from the Big Bang to the modern Universe, bringing us closer to the answer to the main question motivating *NASA's Cosmic Origins* program: *"How did we get here?"*

The proposed methodology

I propose to investigate mergers using a computational approach aiming for direct confrontation with data from observed populations of massive stars. To enable the publication of intermediate results, I will distinguish main sequence and post main sequence mergers. The first group results in so-called *massive blue stragglers:* stars that are too blue and luminous for their age. The second group may result in *blue super giants:* stars that are too big to be main sequence stars and too blue to be helium burning stars, according to standard single stellar models (see Figure 1). For both cases I will break down the problem into different evolutionary steps. A tentative timeline for the different steps is depicted in Figure 2.

Step I: Evolution into contact: With existing stellar evolution codes we can model the evolution of binary stars to determine which systems come into contact and under which circumstances. I have ample experience with different codes that are suitable to do this and I can make use of the >20.000 detailed binary models of close binaries I computed during my Ph.D using a high-performance parallel computing cluster [11, 12]. Combining these results with estimates for the initial distribution functions for binary parameters we can compute which fraction of massive stars will merge with a companion.

Step II: The merger: Most studies about mergers employ three-dimensional hydro-dynamical codes. As such computations typically take between several days to months of computing time, they are not feasible for the purpose of this study. To study the properties of a complete population of stellar merges we need to exploit computationally inexpensive methods, smart algorithms based on results of hydro models, such as the entropy sorting algortithm developed by [13]. This method allows constructing models of merged stars using our computations in Step I as input.

Step III: The evolution: The models produced in step II can be imported back into a stellar evolutionary code to compute its further evolution, see also the next. This method has been developed within the Group where I am currently based [14]. After we computing grids of evolutionary models we can construct a synthetic population to answer *key question I-III* from a theoretical perspective. In this phase we will critically evaluate the effects of uncertain input assumptions taken in step I-III.

This step will result predictions intended for comparison with and interpretation of observations of nearby resolved populations: e.g. the distribution of stars in the colour magnitude diagram, their surface abundances, rotation rates etcetera. In collaboration with Dr. C. Leitherer (STScI), we will provide predictions for distant unresolved populations, e.g. integrated colours and predictions for the number of supernova and gamma-ray burst for different environments. Furthermore, this step will provide input for other computational studies such as galactic chemical evolutionary models or models of the radiative feedback of massive stars.

Step IV: A confrontation with observations: An excellent opportunity for this project comes from two surveys undertaken by the VLT-Flames consortium of massive stars [15]. This consortium brings together world experts in multi-object spectroscopy, modelling of stellar atmospheres and stellar evolution and includes the STScI staff members Dr. D. Lennon (science contact for this proposal) and Dr. N. R. Walborn. The first survey provided accurately determined rotation rates and surface abundances for massive stars in environments and raised some of the key questions of this proposal (Figure 1). The ongoing Tarantula survey [16] will result in well-determined parameters for about a thousand massive stars — the largest homogeneous sample available. Being a member of the consortium myself, I will have access to the data prior to publication. Follow-up observations with the HST are currently being planned.

Computational tools

This project is computationally challenging, due to two requirements: (I) we want to model the physical processes in a high level of detail, which typically requires long computing times and at the same time (II) we want to compute a very large number of models for binaries with different initial parameters to be able to compare with observed populations and to properly evaluate the uncertainties in our models. Instead of making a compromise, we will employ three state-of-the-art evolutionary codes, which are highly complementary, see Table 1. **The First code (BEC)** is unique as it takes into account detailed physical processes, such as mixing induced by rotation, as well as the interaction with a companion star. In De Mink et al (2009a, [11]), I showed that including these effects lead to the discovery of a new binary evolutionary scenario, which we propose to explain the intriguing high-mass X-ray binaries, such as M33 X-7 [18]. In De Mink et al (2009b, [17]) I used this code to demonstrate that massive binaries can efficiently pollute their environment and I argue that massive binaries are likely to be the main source of the abundance anomalies observed in globular clusters. **The second code (TWIN)** is fast, even though it solves the complete set of differential equations needed to compute the structure and evolution of both stars and their orbit. In De Mink et al. (2007, [12]), I showed that it is feasible to use this code on a parallel high-performance computer cluster to compute over ten thousands binary models. In Glebbeek, Gaburov, De Mink et al (2009, [18]) we used this code to investigate the potential formation of intermediate-mass black holes via multiple stellar collisions. **The third code (BSE)** holds probably the world record for speed. It has been designed to perform population synthesis. It relies on analytic fits based on detailed evolutionary models. In Lugaro, De Mink, Izzard et al (2008, [19]) we used this code to investigate the most metal-poor, but surprisingly carbon-rich stars residing in the halo of our galaxy. In De Mink, Izzard, Langer (in prep.) I use this code to investigate the origin of the rotation rates of massive stars.

Motivation intstitute and Collaborators

I propose to undertake this project at the Space Telescope Science Institute in Baltimore. My science contact here is Dr. D. Lennon, with whom I am already collaborating within the VLT-flames consortium of massive stars. His profound insight in the VLT-flames dataset will be extremely valuable for this project. Furthermore, I will work with Dr. C. Leitherer. His expertise in stellar atmospheres and his interest in starburst galaxies will help to take this project beyond the nearby resolved stellar populations, such that we can make predictions for the most distant starforming regions that Herschel and the James Web Space Telescope will probe.

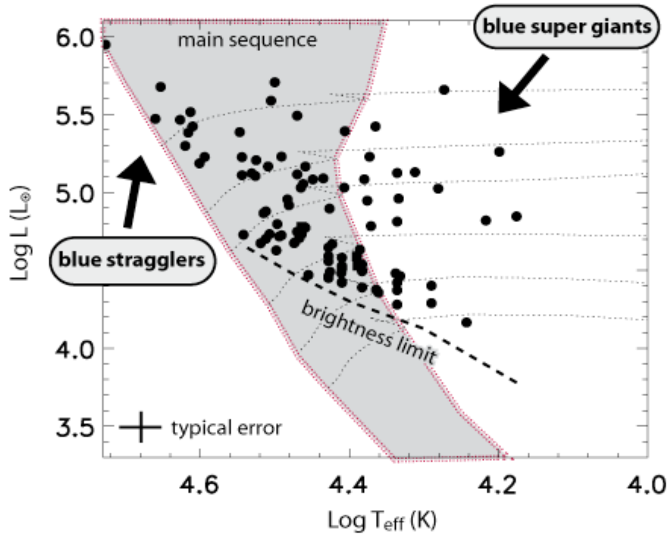

Figure 1: The brightest stars in the cluster N11 observed by the VLT-Flames massive star consortium [15]. Standard models of single stars (thin lines) do not reproduce the distribution of stars in this diagram. They predict a steep drop-off at the end of the main sequence (dark-grey area), while a gradual distribution is observed, with many blue super giants residing beyond the end of the main sequence.

This discrepancy is found for many young stellar populations and may reflect the fact that many massive stars interact with a companion star. For example, mergers resulting from very close binaries (orbits less than 5 days) may appear as *"blue stragglers".* Mergers resulting from wider binaries (orbits of approx. 5-500 days) may appear as "*blue super giants*".

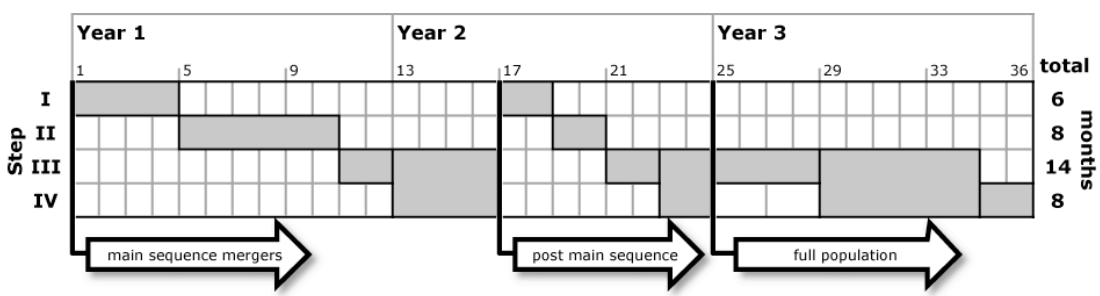

Figure 2: Tentative time line. I will first investigate main sequence mergers, taking step I-IV. After developing the methods and gaining experience I will be able to study mergers of post main sequence stars in less time. The final year will be devoted to combine the results predictions for a complete population.

ID	Description	Comp. time	speed	physics	developers
1	**BEC:** Detailed hydro-dynamical stellar evolution code, including the effects of rotation, magnetic fields, mass transfer and tides and an extended chemical network.	10 hours	+/-	++	*N. Langer, A. Heger, S.-Ch.Yoon,*
2	**TWIN**: Implicit binary evolution code using a non-Lagrangian adaptive mesh, solving simultaneously for the structure, composition and orbital equations.	1 hour	+	+	*P. Eggleton, O.R. Pols, E.Glebbeek*
3	**BSE:** Rapid code using analytic approximations based on detailed stellar models. Suitable for population studies and testing effect of input assumptions.	1 second	++	+/-	*R.G. Izzard, J. Hurley, O.R. Pols*

Table 1 The complementary codes, which will be used in this project. The average time needed to compute one binary evolutionary model is given as well as a subjective indication of the performance of this code with respect to the two main requirements for this project: speed and physics

References

[1] Kobulnicky, H. A. & Fryer, C. L., ApJ 660, 747, 2007
[2] Sana, H., Gosset, Naze et al. MNRAS 386, 447, 2008
[3] Wellstein S., Langer, N. A&A, 350, 184, 1999
[4] Pols, O.R., A&A 290, 119, 1994
[5] Yoon, S-Ch., Langer, N., A&A 443, 643, 2005
[6] Woosley, S. E.; Heger, A., Apj 634, 914, 2006
[7] Tanvir, N. R. , Fox, D. B. , Levan A. J. et al. Nature 461, 1254
[8] Salvaterra, R. Della Valle, M. Campana, S. et al. Nature, 461, 1258
[9] Podsiadlowski, Ph.; Morris, T. S.; Ivanova, N. ASPC,355, 259, 2006
[10] Figer, D. F., MacKenty, J. W., Robberto, M., et al. ApJ, 643, 1166, 2006
[11] De Mink, S.E., Cantiello, M., Langer N. et al A&A, 497, 243, 2009
[12] De Mink, S.E., Pols, O.R., Hilditch, R.W., A&A 467, 1181, 2007
[13] Gaburov, E.; Lombardi, J. C.; Portegies Zwart, S. MNRAS, 383, 5, 2008
[14] Glebbeek, E. PhD thesis, Utrecht University, 2007
[15] Evans, C. J., Smartt, S. J., Lee, J.-K. et al., A&A 437, 467, 2005
[16] Evans, C. J.; Bastian, N.; Beletsky, Y. et al. (De Mink, S.E. . 9^{th} of 40 authors), IAUS 266, 2009, arXiv:0909.1652
[17] De Mink, S.E., Pols, O.R., Langer, N., Izzard, R.G., A&A, in press, 2009
[18] Glebbeek, E.; Gaburov, E.; De Mink, S. E, Pols, O.R., Portegies-Zwart, S. A&A 497, 255, 2009
[19] Lugaro, M., De Mink, S.E., Izzard, R.G., et al. A&AL, 484, 27, 2008