The Impact of Massive Binaries through the Cosmic Ages

This project aims to understand and quantify how binarity affects the role massive stars play in the Universe through feedback and as tracers of star formation in the high redshift Universe.

Massive stars shape the Universe: with their high luminosities, strong stellar winds and violent deaths, they pollute and stir their surroundings, in which new stars and their planets form. As such they can be considered as cosmic engines that played a major role in transforming the pristine Universe left after the Big Bang to the modern Universe in which we live today.

Massive stars do not live their lives alone (e.g. Mason et al 2009). Observing campaigns of nearby young clusters show that *the majority of massive stars is member of a very close binary system in which mass exchange is inevitable* as the stars evolve and expand (e.g. Sana & de Mink et al. Science 2012, see Fig. 1). This drastically changes the fundamental properties of both stars (brightness, color, ionizing flux, chemical yields, X-rays etc.) as well as their final fate as core-collapse supernovae, pair-instability supernova and gamma-ray bursts, constituting the brightest explosions probing the distant Universe with current records at redshifts of 3.9 (Cooke et al. 2012) and 9.4 (Cucchiara et al. 2011).

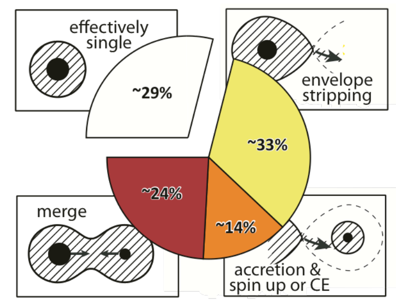

Fig 1: Fraction of massive stars that will interact with a companion before they die by stripping, accretion or mergers. Based on an extensive monitoring campaign of Galactic O-stars, resulting in a sample of orbital solutions that exceeds all previous work in completeness. This implies that **only a minority of massive stars will live its undisturbed** (Sana & de Mink et al. Science 2012).

At high redshift binarity is likely to have a disproportionally large impact for three reasons. → First of all, on average the metallicity is lower and stellar wind mass loss is reduced (e.g. Vink et al. 2000) such that most single stars retain their hydrogen envelope. In contrast, a star in a binary can be stripped directly by a companion or as the indirect consequence of angular momentum gain. This results in hot and compact stars that are sources of radiation that can ionize hydrogen as well as helium. → Secondly, binary interaction is very efficient in producing fast rotating stars (e.g. de Mink et al. 2012a). At low metallicity, massive stars are very sensitive to mixing induced by rotation, see Fig.2. This affects their spectra and chemical yields, and may lead to long gamma-ray burst (Maeder & Meynet 2000, Yoon et al. 2006, Brott & de Mink et al. 2011). → Thirdly, at low metallicity stars leave behind more massive remnants. If these compact objects accrete mass from a companion they give rise to very luminous X-ray sources, which may be important sources of heating and reionization of the intergalactic medium (Mirabel et al 2011, Fragos et al. 2012).

I propose to investigate the implications of our new insight in the massive star binary fraction on the integrated properties of young stellar populations to address the following questions:

➔ **Q I:** ***How does binarity affect the role of massive stars as cosmic engines?*** How does it affect the radiative, mechanical and chemical feedback of massive stars (e.g. ionizing radiation, X-rays, winds, yields, explosions)? Do binaries play a role in heating and reionization at cosmic dawn?

➔ **Q II:** ***How does binarity affect the role of massive stars as cosmic probes***? How does accounting for the effects of binarity in population synthesis models affect the inferred initial mass functions, mass-to-light ratios, metallicity indicators and cosmic star formation rate (Madau et al. 1996)?

➔ **Q III:** ***Do binaries power the most luminous explosions***? E.g. do long gamma-ray bursts result from massive binaries? Can binary mergers produce pair-instability supernova in the local universe?

This program addresses several of the key topics of the NASA's *Physics of the Cosmos program* by making the connection between massive stars, transients and compact objects and feedback at high redshift. I propose to use undertake this project using theoretical models seeking direct confrontation with observations in particular the Chandra deep fields (Brandt et al. 2001, Giacconi et al. 2002, Lehmer et al. 2005) as well as local starforming galaxies observed by Chandra (e.g. López-Sánchez & Esteban 2010).

There has been no lack of interest in studying the physics of binary systems, most prominently in the context of type Ia supernovae and gravitational wave sources. However, the exploration of the effects of binarity on stellar populations – nearby and at high redshift – is still in its infancy. Our insight in the properties of distant galaxies relies almost exclusively on synthesis models in which massive stars are treated as single stars (e.g. STARBURST99, GALEXEV).

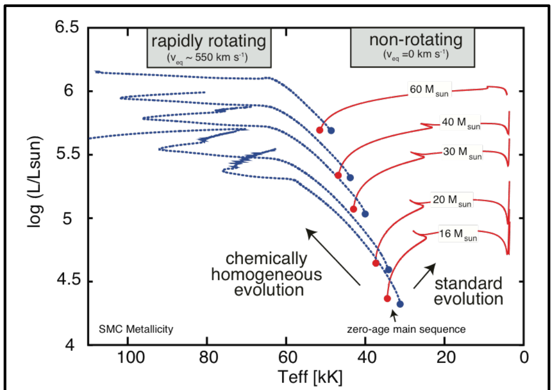

Fig 2: The effect of very rapid rotation on the evolutionary tracks of massive stars at low metallicty (Brott & de Mink et al. 2011). Mixing induced by rotation can lead to chemically homogeneous evolution, i.e. stars that evolve towards higher luminosities and temperatures. This evolutionary path has been for the formation of long gamma-ray burst progenitors (Yoon & Langer 2005, Woosley & Heger 2006).

Pioneering work exploring various aspects of the impact of binarity is appearing gradually, illustrating the increased interest in particular for X-ray binaries (for example Belkus et al. 2003, Han et al. 2007, Power et al. 2009, Mirabel et al. 2011, Eldridge 2012, Li et al. 2012, Fragos et al. 2012, Justham & Schawinski 2012, Zhang et al. 2012). These studies are important steps forward. However, many of these studies are purely based on population synthesis codes that use approximate schemes. They do not match the current state-of-the art in the massive star community and they do not account for the latest insight in the binary frequency among massive stars.

Computational tools and Calibration: The evolution of a single star is almost completely determined by its initial mass. In contrast, the evolution of a star with a binary companion depends on additional parameters: the mass ratio, separation and eccentricity. The large parameters space makes this project computationally challenging. At the same time, new uncertainties are introduced regarding the input assumptions (binary fraction, distribution of initial parameters and how these depend on metallicity) as well as the treatment of the physical processes (e.g. efficiency of mass and angular momentum transfer, common envelope evolution, stellar mergers). To address these challenges I propose to combine the strength of different codes that are highly complementary in terms of speed and the level of detail in which the physics is treated (see Table 1). These codes come in two types

I. **Detailed state-of-the-art stellar evolutionary codes** that solve the stellar structure equations and account for mixing processes and well as binary interaction, etc (**STERN** & **TWIN**)
II. **Population synthesis code**, which allows to explore the parameter space and the effect of uncertain input assumptions (**BINARY_C**)

For this project I will use detailed stellar evolution models (such as the grids published De Mink et al. 2007, 2009, Brott & de Mink et al 2011 as well as new model grids) to ensure that the population synthesis code adequately accounts for all relevant processes (as I have done for example in De Mink et al 2012a to account for the effects of rotation). The simulated populations will be tested against various observational datasets including: (I) large homogeneous surveys of resolved stars (such as the Tarantula Survey in which I am actively involved (Evans et al., 2011), (II) local and distant star forming galaxies observed by Chandra spanning a range of metallicities, (e.g. López-Sánchez & Esteban 2010, Lehmer et al. 2010). Independent test for the final stages will be provided by the transient surveys (such as the Palomar Transient Factory, e.g. Arcavi et al. 2010, and PAN-STARRS). This will provide new observational constraints that can be used to improve the detailed models as well as the population synthesis models.

Experience: I have ample experience as a co-developer with the three codes I intend to use for this project giving me thorough insight in their strengths and limitations. During my PhD and as an Argelander Fellowship I worked with **STERN** which is, to my knowledge, the only well-tested code that includes a state-of-the-art treatment of the effects of rotation and can simultaneously treat the physics of binary

Description	Computing time (CPU)	Convergence late stages	Physics	Main developers
I) STERN: Detailed hydro-dynamical stellar evolution code, accounting for effects of rotation, magnetic fields, mass transfer, tides and an extended chemical network.	>10 CPU hours	●●○○○	●●●●●	*N. Langer, A. Heger, S.-Ch.Yoon,*
I) TWIN: Detailed implicit binary evolution code using a non-Lagrangian adaptive mesh, solving simultaneously for the structure, composition and orbital equations.	~1 CPU hour	●●●○○	●●●●○	*P. Eggleton, O.R. Pols, E.Glebbeek*
II) BINARY_C: Population synthesis code using approximations based on detailed stellar models. Suitable for population studies and testing effect of input assumptions.	<1 CPU second	●●●●●	●●○○○	*R.G. Izzard, J. Hurley, O.R. Pols*

Table 1: An overview of the complementary codes that will be used in this project expressing convergence during the late evolutionary stages and the level of detail of the treatment of the physics on an qualitative 5-point scale.

interaction[1]. I lead an investigation of the interplay of effects of rotation and binarity, leading a surprising discovery of a new evolutionary channel that can explain the formation of certain very massive X-ray binaries (de Mink et al 2009a). I also used this code to demonstrate the very promising potential role of massive binaries in explaining the mysterious presence of multiple populations in globular clusters (de Mink et al. 2009b). Recently, we published a new extensive grid of rotating stellar models (Brott & de Mink et al. 2011, see Fig. 2). Using a population synthesis code based on these models we derived new constraints on rotational mixing (Brott et al., incl. de Mink, 2011).

Earlier, I wrote routines to use the detailed evolution code **TWIN** on high performance computing cluster to compute one of the largest grids of detailed interacting binary models at that time (de Mink et al 2007) using high-performance computing cluster. By testing against a large sample of eclipsing binaries I tested one of the main uncertainties, the efficiency of mass transfer (de Mink et al 2007). We also used this code to simulate the evolution of very massive stars that result from a sequence of stellar mergers in the dense center of a globular cluster (Glebbeek, Gaburov & de MInk et al., 2009). More recently, I co-supervised a student to study the progenitors of type IIb supernovae (Claeys & de Mink et al. 2011).

As a Hubble fellow at the Space Telescope Science Institute and Johns Hopkins University I became interested in simulating stellar populations. I co-developed, tested and optimized a binary population synthesis code **BINARY_C** (Izzard et al. 2004, 2009, de Mink et al. 2012a) based on prescriptions by Hurley et al (2002). This code approximates the evolution and interaction processes to gain computational speed. I had used an earlier version of this code to investigate the peculiar abundances of the old population of low-mass metal-poor stars in the halo (Lugaro & de Mink et al, 2008, Abate et al. incl. de Mink, 2012). Recently, I have implemented new prescriptions to treat the main effects of rotation, and an improved treatment of mass gainers and mergers. This lead to the first to papers in which I address the following question: Are the rotation rates of early-type stars the consequence of star formation, evolutionary binary interaction? (de Mink et al. 2012a) and I estimated the incidence of mergers and mass gainers among the early-type stars in the Galaxy (de Mink et al. 2012b).

Work Plan and Tentative timeline: The three key questions that I aim to address (see page 1) can be devided in sub projects that are relatively independent. Fig. 3 depicts a tentative timeline, which will be evaluated and adapted Id needed depending on process and unforeseen developments. I plan to start in the first year with two subprojects that potentially have large impact, but which are fairly simple and low-risk. They can be undertaken without modifying the codes. These concern a first estimate of the effect of binarity on the ionizing flux and mechanical feedback (Ia & Ib). During this time I will orient myself and explore the possibility of new collaborations within the institute in particular concerning radiative and X-ray feedback (Ic) for which I reserve most of the second year. To enable more reliable comparison with data and study the effect of binarity on various diagnostics (II) In the mean time, I will work on mapping spectral libraries. This is relatively straight-forward since I but does require some mod-

[1] The open source code MESA (Paxton et al. 2011) is promising, but the physics required for this project is not yet well tested.

ifications to the code. A potential challenge, where I aim for significant improvement of existing work is the treatment of the spectra of the stripped stars. Toward the end of the second year I hope to have time to work on the explosive end points (III). Using one of the detailed codes I will explore the progenitors of pair instability supernova resulting from binaries. Using these results I can revisit the effects on chemical feedback in the final year. Throughout the project I will spend a fraction of my time to provide my expertise to observational programs with the in which I am involved and which I will use to calibrate my models.

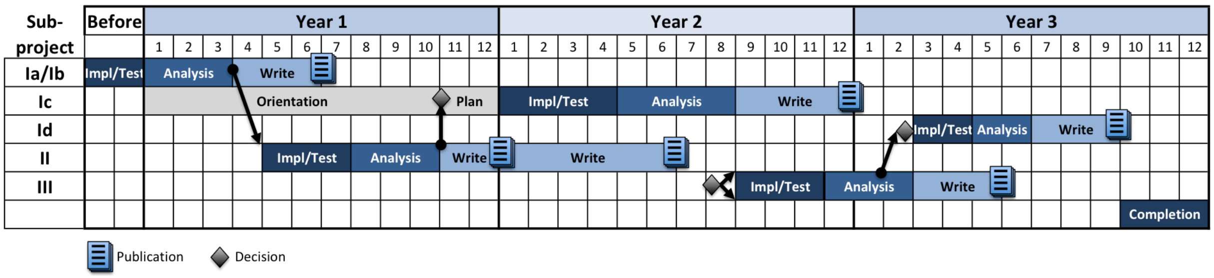

Fig 3: Tentative timeline of the different subprojects. Ia/b: radiative and mechanical feedback, Ic X-rays and feedback, Id Chemical feedback, II Spectral synthesis and diagnostics, III Explosive end points. Each project consist of four phases which may overlap: an orientation and planning phase, an implementation and testing phase, the main analysis and preparation of the results for publication .

Collaboration at MIT:

Given the scope of the project and the aim to bridge the gap between different communities this program require interaction with experts in different areas. My preference is to conduct this program at MIT where I can work with Dr. S. Rappaport. He has extensive experience with both the detailed modelling binary systems as well as population synthesis studies. In particular, I hope to benefit from his epertise with the evolved stages and for example the ultra luminous X-ray sources. Furthermore, I would be interested in interacting with Dr. R. Simcoe, in particular because of his expertise of enrichment of IGM, and Dr. A. Frebel, who is employing metal-poor stars in the galactic halo as a window on the earliest stellar generations. Furthermore the institute hosts several people who work or have worked on compact objects in binary systems (Dr. H. Bradt, Dr. D. Chakrabarty, Dr. G. Clark, Dr. P.C. Joss).

The vicinity to CfA will allow further interaction concerning various aspects of this project. I am interested in interacting with various members of the institute for theory and computation, in particular Dr. A. Loeb for his expertise and Dr. R. Narayan) as well as the high energy department, e.g. Dr. G. Fabbiano and Dr. A. Zesas for their expertise with X-ray binary populations, Dr. A. Soderberg for constraints on supernova progenitors and Dr. E. Berger for his interests in gamma-ray burst and involvement in transient searches.

I also intend to maintain my external contacts in particular: C. Leitherer (STScI), J. Eldridge (Auckland), P. Posdiadlowski (Oxford, UK), C. Norman and J. Silk (Johns Hopkins), various members of the Massive Star group in Bonn (Langer, Yoon, Izzard) the MESA team in Santa Barbara, Ca (e.g. B. Paxton, L. Bildsten) and the members of the VLT-Flames collaboration.

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