SF2A 2019
P. Di Matteo, O. Creevey, A. Crida, G. Kordopatis, J. Malzac, J.-B. Marquette, M. N'Diaye, O. Venot (eds)

EVOLUTION OF MASSIVE STARS AND BINARY SYSTEMS AS PROGENITORS OF GRAVITATIONAL WAVES EMITTERS

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Abstract. In this contribution we give a brief overview of the effects of rotation, stellar winds, metallicity and binarity on the evolution of massive stars. We focus on the role of these parameters in shaping the end states of stellar evolution. Special attention is given to the mass of the stellar remnants that has been questionned by the detection of heavy black holes in merger events leading to gravitational waves emission.

Keywords: Stars: massive, Stars: rotation, Stars: mass loss, Stars: binary, Gravitational waves

1 Introduction

The detection of gravitational waves from binary black hole mergers by the LIGO-VIRGO collaborations has revealed surprisingly high masses for the black holes involved (Abbott et al. 2016, 2017a,b). With masses in excess of 15 $M_\odot$ and reaching about 40 $M_\odot$, such black holes are more massive than those detected so far in X-ray binaries and for which masses do not exceed 15 $M_\odot$(Kharghara et al. 2010; Orosz et al. 2011), with values typically around 5 to 10 $M_\odot$. This raises the question of the conditions required to form such black holes in the framework of massive stars evolution.

The evolution of massive stars, and thus the end states and the properties of the compact objects, depend crucially on rotation, mass loss, metallicity, the presence of a companion. In the following we will summarize the main effects caused by these processes. We will focus on the properties of the stellar core prior to supernova explosion, as well as on the remnant masses. Exhaustive reviews on the evolution of massive stars are found in Maeder & Meynet (2000); Langer (2012). We refer the reader to e.g. Keszthelyi et al. (2019) for a summary of the effects of magnetic fields, which are expected to be important for about 5-10% of massive stars (Grunhut et al. 2017).

2 Stellar rotation

Rotation affects the evolution of massive stars in various ways. First, due to the geometrical deformation, the equatorial radius is larger than the polar radius. Given the definition of effective temperature, this means that it is not uniform over the surface. Quantities depending directly on $T_{\rm eff}$ (and $logg$, such as the flux of ionizing photons) are thus also varying with latitude. Departure from sphericity triggers large scale motion (the Eddington-Swift circulation) that efficiently transports angular momentum from the core to the surface. Differential rotation between layers located at different radii triggers additional mixing processes (e.g. shear turbulence) that convey both anguar momentum and chemical species from the inner to the outter regions of the star.

These general effects impact the star's properties and evolution. Except on the zero-age main sequence, the luminosity of a rotating star is increased compared to a non-rotating star. Mixing processes extend the size of the convective core which increases the lifetime of the successive burning sequences (H, He, C...). A natural consequence is the increase of the mass of the CO core, and thus of the remnant. Limongi & Chieffi (2018) estimate that at low metallicity and below about 60 $M_\odot$ the CO core mass can be multiplied by a factor $\sim$1.5 due to rotation (see their Fig. 18). The conversion of the CO core mass to the remnant mass depends on the

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assumptions used for the explosion: either a fixed amount of ^{56}Ni (usually 0.1M$_\odot$) is assumed to be produced, or direct collapse to a black hole is considered. The range of remnant mass is thus very wide, from about 1 to ∼80 M$_\odot$ according to Limongi & Chieffi (2018). Uncertainties on the CO core-remnant mass transformation dominate the error budget on the final compact object mass.

3 Mass loss

Massive stars experience strong mass loss of different nature. For O and B stars, the winds are radiatively driven by acceleration through numerous metallic lines (Castor et al. 1975). The same mechanism is probably at work in Wolf-Rayet stars. For cool red supergiants, no theory exists so far to explain the large mass loss whose measurements are highly uncertain (e.g. Mauron & Josselin 2011). Episodic huge mass ejections of debated nature happen in luminous blue variables. Mass loss is one of the main drivers of massive stars evolution (Chiosi & Maeder 1986). It affects the internal structure, lifetimes, remnant masses, among others. For instance, Georgy (2012) showed that changing the mass loss rates of red supergiants within the range of measured values leads to different progenitors of type II supernovae (i.e. blue, yellow or red supergiant progenitors).

This highlights the importance of quantifying accurately mass loss rates in different phases of evolution. Various prescriptions exist, based either on observational results or theoretical predictions. Renzo et al. (2017) performed a systematic study of the effect of varying these prescriptions in stellar evolution models. They showed that the final masses could change by 15 to 30%. If in addition a scaling is applied to take into account "clumping" (i.e. the fact that stellar winds are not homogeneous), variations up to more than 50% can be expected on final masses (see their Fig. 1).

4 Metallicity

The metal content of massive stars affects their evolution in the following two main ways. First, due to reduced opacities, low metallicity stars are more compact and hotter. The reduced size implies stronger gradients, which increases the efficiency of mixing processes due to rotation. Second, radiatively-driven winds are by nature metallicity dependent. Mass loss rates depend on Z^{α}, whith α between 0.7 and 0.8 (Mokiem et al. 2007; Vink et al. 2001). Consequently, lower metallicity stars lose less mass and produce more massive compact objects.

Groh et al. (2019) computed evolutionary models at $1/30^{th}$ solar metallicity and obtained CO core masses up to 70 M$_\odot$ (for initial masses of 120 M$_\odot$). The corresponding remnant masses are as high as 20 M$_\odot$. Limongi & Chieffi (2018) find similar CO core masses. From these calculations, it is clear that the heavy black holes detected by the LIGO-VIRGO detections should have been formed at low metallicity. At solar metallicity, Groh et al. (2019) do not produce remnants with masses higher than 10 M$_\odot$.

5 Chemically homogeneous evolution

From the effects described in the two previous sections, a favorable situation to form high mass remnants is when fast rotation is combined with low metallicity. Both cases increase the core size and the remnant mass. In these conditions, a peculiar evolutionary channel may occur: quasi-chemically homogeneous evolution (Maeder 1987; Langer 1992; Yoon et al. 2006). Actually, it should occur with the single condition that the star rotates fast enough, but this is favoured at low metallicity due to reduced mass and angular momentum loss. If rotation is fast enough, the timescale for mixing processes may become shorter than the nuclear timescale, implying that material synthetized in the core is immediately transported to the surface. The chemical composition is thus quasi homogeneous. This implies a reduction of the surface opacity, and consequently a higher effective temperature. At the same time the mean molecular weight increases and so does the luminosity. As a consequence the star evolves to the blue side of the Hertzsprung-Russell diagram, and remains compact, contrary to normal evolution in which the surface cools down and the star expands (e.g. Brott et al. 2011; Szécsi et al. 2015).

This type of evolution may lead to rapidly rotating CO core, prior to supernova explosion. It is thus a good candidate to form progenitors of long-soft gamma-ray bursts (Yoon et al. 2006). The properties of some Wolf-Rayet stars in the Galaxy and the Magellanic Clouds may be compatible with quasi-homogeneous evolution (Martins et al. 2009; Bestenlehner et al. 2011; Martins et al. 2013). The preference for low metallicity of LGRB hosts (e.g. Palmerio et al. 2019) also argues in favour of this type of evolution.

The formation of binary black holes may require quasi-chemical evolution as claimed by Mandel & de Mink (2016). In the following we describe the effects of binarity on stellar evolution and come back to this scenario.

6 Binarity

The presence of a companion can affect significantly the evolution of a massive star, provided the companion is close enough. There are two main categories of effects at play: tides and mass transfer. The former trigger energy exchange and modification of the internal structure (Zahn 1989; Mathis & Remus 2013). This can lead to spin-up or spin-down of the stars, and ultimately to synchronization of the stellar and orbital periods (Zahn & Bouchet 1989). The transport of angular momentum and chemical species due to rotation is thus affected. Mass transfer has the same effects as mass loss through winds, but can be more efficient. It does not depend (in principle) on metallicity and is accompanied by transfer of chemicals and angular momentum. Parameters governing mass transfer (efficiency, geometry) are poorly known, leading to uncertainties on its effects. Both tidal and mass transfer effects depend on the orbital parameters (stellar mass ratio, separation, eccentricity). The evolution of binary systems is thus even more complex than that of single stars.

de Mink & Belczynski (2015) performed a systematic study of the effects of various binary parameters on the merger rate of black hole-black hole systems. Their conclusion is that this rate is actually dominated by uncertainties on the mass function, rather than on specific binary parameters.

The formation of compact objects binary systems like those leading to mergers detected by the LIGO-VIRGO collaborations is classicaly explained by a phase of common-envelope evolution (Postnov & Yungelson 2014). This is briefly summarized on the left side of Fig. 1. After the primary has exploded as supernova the secondary expands, fills its Roche lobe and engulfs the compact object formed from the primary. During the common envelope phase, the envelope is ejected, leading to a system in which the secondary core subsequently explode as supernova. A double compact object system is formed. This channel assumes that the successive supernova events do not disrupt the system, and that during the common-envelope phase the compact object does not merge with the secondary's core. The common-envelope phase is required to shrink the orbit by dynamical friction.

To overcome the latter possibility, Mandel & de Mink (2016) have considered the possibility that chemically homogeneous evolution is followed by the binary's components (see also Song et al. 2016). The rationale for this scenario is that tidal interaction may spin-up stars sufficiently to encounter the conditions for homogeneous evolution, even if the initial rotational velocity of the individual components was not sufficient. The stars thus remain compact and avoid the common envelope phase, leading to a higher probability to remain bound until the double compact object phase. This is illustrated on the right side of Fig. 1. Another advantage of this channel is that much less mass is lost from the system (since there is no mass transfer). Consequently, remnants of higher masses are expected. The major uncertainty of this model lies in the conditions required to produce chemically homogeneous evolution. The internal rotation profile and its modificationby transport mechanisms during stellar evolution seem to be a key parameter (Brott et al. 2011; Song et al. 2016; Cui et al. 2018; Song et al. 2018). Song et al. (2016) predict that chemically homogeneous evolution in binary systems is favoured at high metallicity, when stars are less compact than at lower metallicity and thus more prone to experience tidal effects.

According to Mandel & de Mink (2016) the binary scenario involving chemically homogeneous evolution predicts a maximum merger rate at a redshift of about 0.5 but basically no event at high redshift. Equal-mass systems are also favoured, contrary to the common-envelope scenario.

7 Conclusions

The evolution of single and binary massive stars is rather complex and depends on many parameters: rotation, mass loss, metallicity, binary parameters, mass transfer properties, not to mention magnetic field. In the case of single stars, lower metallicity favours higher masses for the stellar remnants. The range of masses constrained by the gravitational wave merger events is accounted for only by low metallicity single star evolutionary models. In the binary scenario involving chemically homogeneous evolution, higher metallicity seems to be favoured. In that respect, the identification of the host environments of gravitational wave events will likely bring constraints to the evolution of massive stars. The redshift distribution of compact objects mergers will also shed light on the evolution of massive binary systems.

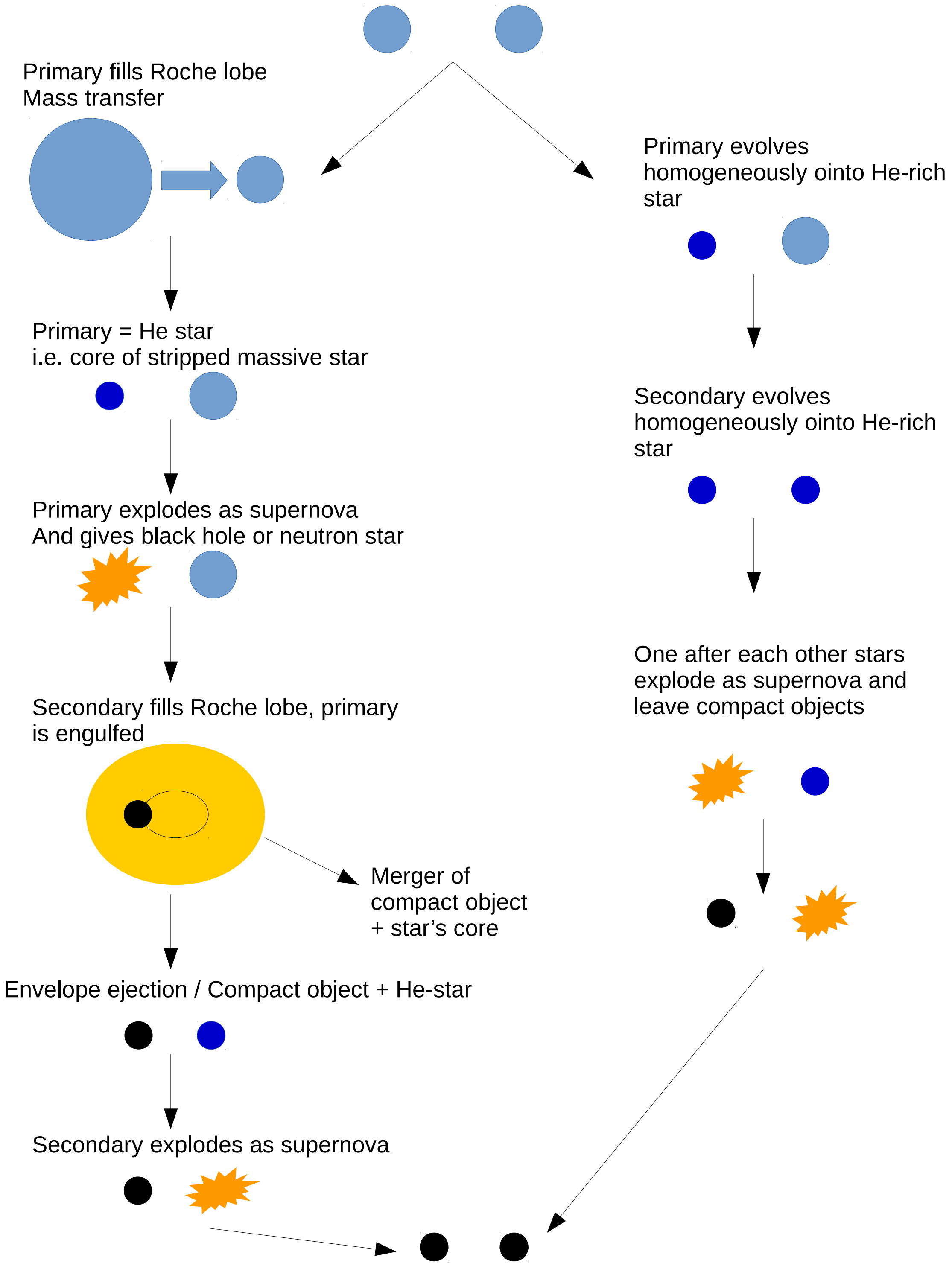

Fig. 1. Sketch of the two channels expected to form compact objects binaries. The left side is the “classical” channel involving a phase of common envelope evolution. The right side is the channel involving chemically homogeneous evolution. Adapted from Postnov & Yungelson (2014) and Mandel & de Mink (2016).

We thank the organizers for the invitation.

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