Serb. Astron. J. № 201 (2020), 1 - 13
DOI: https://doi.org/10.2298/SAJ2001001P

UDC 524.387–54
Invited review

THE EVOLUTION OF MASSIVE BINARY SYSTEMS

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(Received: November 16, 2020; Accepted: November 16, 2020)

SUMMARY: The evolution of massive stars in close binary systems is significantly different from single star evolution due to a series of interactions between the two stellar components. Such massive close binary systems are linked to various astrophysical phenomena, for example Wolf-Rayet stars, supernova type Ib and Ic, X-ray binaries and gamma-ray bursts. Also, the emission of gravitational waves, recently observed by the LIGO-Virgo detectors, is associated with mergers in binary systems containing compact objects, relics of massive stars - black holes and neutron stars. Evolutionary calculations of massive close binary systems were performed by various authors, but many aspects are not yet fully understood. In this paper, the main concepts of massive close binary evolution are reviewed, together with the most important parameters that can influence the final outcome of the binary system evolution, such as rotation, magnetic fields, stellar wind mass loss and mass accretion efficiency during interactions. An extensive literature overview of massive close binary models in the light of exciting observations connected with those systems is presented.

Key words. Binaries: close – Stars: massive – Stars: Wolf-Rayet – Gamma-rays: bursts – Gravitational waves

1. INTRODUCTION

Massive stars evolve through all core nuclear burning stages up to the formation of an iron-nickel core. While fusion of elements lighter than iron releases energy, iron fusion consumes it. With no energy source to balance gravity, the stellar core collapses. Depending on its mass, a star collapses into a neutron star or a black hole while the layers outside of the core are ejected in a supernova (SN) explosion. Since nuclear fusion reactions that produce elements heavier than iron require more energy than they release, such reactions do not occur in stellar cores, but only in supernova explosions. In addition to making elements, supernova explosions scatter them out into the interstellar medium.

The minimum initial mass of a single star at solar metallicity needed to produce an iron core is about 10 $M_\odot$ (Poelarends et al. 2008). In binary systems, the value of the minimum initial mass depends on other initial parameters, such as orbital period and mass ratio of the stellar components. In case of the closest systems, this initial mass limit can be up to 15 $M_\odot$ (Wellstein et al. 2001).

A significant fraction of massive stars are found in multiple systems. Large surveys in different environments suggest that 50% to 70% of all massive stars (Sana et al. 2012, Kiminki and Kobulnicky 2012, Kobulnicky et al. 2012, 2014) are in binary (or multiple) systems where the components are close enough to undergo interaction at least once during their lifetime. Additionally, Sana et al. (2012) indicated that about 70% of massive binaries have orbital periods shorter than 1500 days and estimated that about one third of those stars will merge during their evolution. The orbits of massive close binaries are most likely tidally circularized (Hurley et al. 2002) and eccentricity is not an important parameter to consider.

In general, a massive star in a close binary system evolves significantly different from a single isolated

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star with the same mass and chemical composition. The binary evolution is influenced by the modified gravitational and radiation field and the centrifugal force contribution arising from the rotation of the system. Most importantly, in certain evolutionary phases, mass transfer from one star (mass donor) to the other star (mass accretor or gainer) can occur, changing the physical properties of both stars and in this way also their future evolution and the final fate.

A star in a binary system can start transferring mass to its companion during different phases of evolution (Kippenhahn et al. 1967). Depending on the initial mass ratio, the system may evolve through stable mass transfer or the mass gaining companion may expand significantly, which results in a contact configuration.

The interest in the evolution of interacting binaries increased during the sixties and seventies of the 20th century, also because of the indication that Wolf-Rayet (WR) stars lose their hydrogen rich envelopes due to the Roche lobe overflow (RLOF), i.e. mass transfer to the other companion in a binary system. In other words, mass transfer in binary systems was recognized as a process that can remove a significant amount of matter from a star (Kuhi 1973, Vanbeveren 2009).

Since then, the evolutionary models of massive close binaries have been calculated by many authors. However, many aspects of binary evolution are not yet fully understood. Those include an exact stellar wind mass loss, accretion efficiency during mass transfer, mechanisms for mass loss from the system, the influence of rotation and magnetic fields, to name just a few.

In recent years, massive close binary systems have been identified as potential sites of many exciting astrophysical phenomena, such as Wolf-Rayet binaries (van der Hucht 2001), X-ray binaries (Chevalier and Ilovaisky 1998) supernovae Ib and Ic type (Podsiadlowski et al. 1992, Smith et al. 2011), long gamma-ray bursts (Fryer et al. 1999) and, most recently, sources of gravitational waves (Abbott et al. 2016a,b,c, 2019).

Many detailed reviews about massive close binary evolution have been published in the previous decades, such as for example, Paczynski (1971), Thomas (1977), van der Heuvel (1978), de Loore (1980), Vanbeveren (1991), Vanbeveren et al. (1998), Langer (2012), de Marco and Izzard (2017), Georgy and Ekstrom (2018). In this review, we will summarize the general physics of massive close binary systems and the most important results from numerical models so far related to Wolf-Rayet + O binaries, long gamma-ray bursts and gravitational waves.

This review is organized as follows: In Section 2 we give basic concepts of massive close binary evolution. Stellar wind mass loss is discussed in Section 3 and rotation and magnetic fields in Section 4. Section 5 presents the overview of the numerical codes for binary stellar evolution. Wolf-Rayet + O binaries are discussed in Section 6, collapsars and long gamma-ray burst progenitors in Section 7 and gravitational wave sources in Section 8. A summary is presented in Section 9.

2. BASIC CONCEPTS OF BINARY EVOLUTION

The Roche lobe is the region around a star in a binary system within an equipotential surface, where the material is gravitationally bound to that star. When one star expands beyond its Roche lobe, matter from it starts flowing to the other component via the so-called first Lagrangian point L_1. This process is called Roche lobe overflow (RLOF). The primary star in a binary system, the more massive component, evolves faster than the secondary and through envelope expansion may reach the radius of its Roche lobe and start transferring mass onto the secondary star. The effective Roche lobe radius depends on the orbital separation a and the mass ratio of stellar components q (Eggleton 1983):

$$R_{\rm l} = \frac{0.49q^{-2/3}}{0.6q^{-2/3} + ln(1+q^{-1/3})}a, \qquad (1)$$

where $q = M_2/M_1$ for the Roche lobe radius of the primary star and $q = M_1/M_2$ for the Roche lobe radius of the secondary star.

When both stars are contained within their corresponding Roche lobes, the binary system is called a detached system. The binary system is called semi-detached if only one star expands to its critical Roche radius and is transferring mass to the another component. If the mass gainer also fills its Roche lobe, the systems is called a contact binary.

A star in a binary can reach its critical Roche radius during different phases of evolution (Kippenhahn et al. 1967). Roche lobe overflow happens because of the expansion of the stellar envelope. This expansion can occur on nuclear, thermal (Kelvin-Helmholtz) and dynamical time scales in order of decreasing length.

The mass transfer rate $M_{\rm tr}$ depends on the amount of mass available in the stellar envelope and the characteristic time scale for the envelope growth τ.

Whether binary systems will evolve via Case A, Case B or Case C mass transfer depends on the initial orbital period. If an initial orbital period is a few days, the first mass transfer occurs while the primary is still a core hydrogen burning star. This is the so-called Case A mass transfer and it consists of a fast and a slow phase occurring on the thermal and the nuclear time scale of the envelope, respectively. After Case A mass transfer is completed, if there was no contact, the primary is a less massive star that finished core hydrogen burning. At the same time, if there was any accretion, the secondary is a rejuvenated main sequence star, which means that it has an increased abundance of hydrogen in its core and also a larger mass.

When the initial orbital period is a few weeks, the binary system evolves via Case B mass transfer. The primary fills its Roche lobe for the first time during the shell hydrogen burning. Since the envelope of the primary is very extended, the thermal time scale is shorter and the mass transfer rate is higher than in Case A. It can reach $\approx 10^{-3}$ $\mathrm{M}_\odot$/yr or even higher values. If contact is avoided, the primary loses most of its envelope and becomes a core helium burning star. At the same time, the secondary becomes a rejuvenated, more massive star.

If Case B mass transfer starts during the earlier phases of the shell hydrogen burning, the stellar envelope of the donor is mostly radiative (Case B_r). The expansion of the star stops when most of the hydrogen rich layers are removed and helium core burning starts. During most of the core helium burning phase, the star is a hydrogen deficient Wolf-Rayet star, contained within its Roche lobe. When the initial orbital binary period is larger, the primary may reach the red giant phase and most of the outer layers may become convective before the onset of mass transfer. A Case B binary where this happens is classified as case B_c and it happens on a dynamical time scale.

Case C mass transfer occurs when the initial period is in the order of years. The primary fills its Roche lobe for the first time after the helium core burning is completed. Mass transfer in Case C also takes place on the shortest - dynamical - time scale.

If mass transfer due to the shell hydrogen burning occurs after Case A already took place, it is called Case AB mass transfer, which proceeds on the thermal time scale of the primary and produces correspondingly high mass transfer rates (Wellstein et al. 2001, Petrovic et al. 2005a). After the helium core burning phase is completed, the star may expand again and a third RLOF, Case ABB mass transfer starts (Kippenhahn and Thomas 1970, Wellstein et al. 2001). In a similar way, if a primary star fills its Roche lobe for the first time during the shell hydrogen burning, the subsequent mass transfer, after the helium core burning is completed, is called Case BB.

Fig. 1 shows an example of binary systems that evolve via Case A, Case AB and Case ABB mass transfer to the iron core formation of the primary star. The evolution of binary systems 30 $M_\odot$ + 27 $M_\odot$, 32 $M_\odot$ + 28.8 $M_\odot$ and 34 $M_\odot$ + 30.6 $M_\odot$ is calculated with the MESA evolutionary code. All systems have an initial mass ratio of 0.9, an initial orbital period of 3 days, assumed accretion efficiency of 10% based on massive binary models of Petrovic et al. (2005a) and metallicity of 0.02.

There are multiple methods to calculate the mass transfer rate in the binary system. The most often used so-called explicit methods are Ritter (1988) and Kolb and Ritter (1990). The mass loss from the Roche lobe filling component through the first Langrangian point is given by Ritter (1988) as:

$$\dot{M} = \dot{M}_0 \exp(R - R_l)/H_p, \tag{2}$$

with:

$$\dot{M}_0 = \rho v_s Q/\sqrt{e}, \tag{3}$$

where H_p is the photospheric pressure scale height, ρ is the density, v_s the velocity of sound and Q the effective cross-section of the stream through the first Lagrangian point according to Meyer and Meyer-Hofmeister (1983). R is a stellar radius and R_l is the critical Roche radius defined in Eq. (1). Kolb and Ritter (1990) is extended a similar scheme to also include the case where the stellar radius exceeds the critical Roche lobe radius.

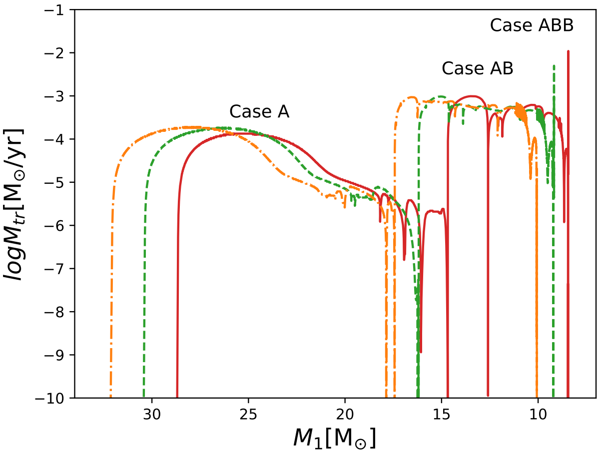

Fig. 1: The mass transfer rate as a function of primary mass in binary systems 30 $M_\odot$ + 27 $M_\odot$ (red solid line), 32 $M_\odot$ + 28.8 $M_\odot$ (green dashed line) and 34 $M_\odot$ + 30.6 $M_\odot$ (orange dash-dotted line) calculated with the MESA evolutionary code. All systems have an initial mass ratio of 0.9, an initial orbital period of 3 days, assumed accretion efficiency of 10% and metallicity of 0.02. They evolve via Case A, Case AB and Case ABB mass transfer to the core iron formation of the primary star.

If the mass transfer rate is not extremely high, the gainer is able to accrete material without a radical expansion and the evolution of such a binary system proceeds via stable mass transfer. If, however, the mass transfer rate is so high that it causes significant expansion of the accretor, the binary system enters a contact phase and a common envelope may form around the binary (de Kool 1990, Iben and Livio 1993). A dynamical spiral-in phase follows, resulting in an ejection of the envelope and a very close binary system or even a merger (Paczynski 1967, Ivanova et al. 2013). Obviously, the evolutionary outcomes of these two scenarios are very different.

One of the major uncertainties in evolutionary calculations of binary systems is the efficiency of mass transfer: what fraction (so called β) of the transferred mass is actually accreted by the secondary star? Conservative evolution assumes that the mass and angular momentum of the binary system are conserved (β = 1) and non-conservative evolution assumes that a fraction of the mass and angular momentum leaves the binary system ($\beta < 1$).

Different assumptions for efficiency of mass transfer are used for modeling by different authors. Conservative models were calculated by, for example, Refsdal and Weigert (1969), Kippenhahn (1969), Paczynski (1971) and more recently by Wellstein and Langer (1999) and Wellstein et al. (2001). Evolutionary binary models where half of the transferred matter leaves the system are done by de Loore and de Greve (1992), de Greve and de Loore (1992). Petrovic et al. (2005a) showed that an efficiency of about 10% is most suitable to explain observed mass ratios in WR + O binary systems.

It is not yet known what the processes are that can expel matter out of a binary system. One possibility is that rotation near the critical velocity leads to a significantly increased mass loss of the donor, which decreases the value of β (Petrovic et al. 2005a).

The understanding of mass and angular momentum transfer and accretion in interacting systems may be essential to explain some of the most exciting cosmic phenomena, which may occur exclusively in close massive binaries: Wolf-Rayet binaries (van der Hucht 2001, Petrovic et al. 2005a), long gamma-ray bursts (Fryer et al. 1999). x-ray binaries (Chevalier and Ilovaisky 1998), Type Ib and Ic supernovae (Podsiadlowski et al. 1992) and gravitational wave sources (Abbott et al. 2019).

To summarize, a close binary system consisting initially of two massive O-type stars eventually enters mass transfer. During this process the mass donor will lose a significant amount of hydrogen from its envelope and the binary system will evolve into a Wolf Rayet + O binary. Wolf-Rayet, helium core burning stars, are characteristic for extremely hot surfaces (50000 K and above), high luminosities (10^5 - 10^6 $L_\odot$) and high stellar wind mass loss rates (10^{-5} - 10^{-4} $M_\odot$/yr).

A Wolf-Rayet star evolves further to a supernova explosion that leaves a neutron star or a black hole as a remnant. At the same time, the secondary is still a main sequence, core hydrogen burning star. After some time, the secondary expands enough to fill its Roche lobe and mass transfer to the compact companion takes place. This phase is observed as a so-called high mass X-ray binary (HXMB). If the compact object is a neutron star, the mass transfer (atmospheric Roche-lobe overflow and wind mass transfer) is most likely unstable, because of the large mass ratio. Such binary systems eventually develop a common envelope that leads to shrinking of the binary orbit.

The secondary will eventually also explode as a supernova, and a double compact object will be created. If any of the hydrogen poor massive components in a binary is rotating fast prior to the supernova explosion (Type Ib/c), a collapsar is formed and long gamma-ray burst occurs. The final remnants of a massive binary evolution, double compact objects, have been recently associated with gravitational waves emission, observed by the LIGO-Virgo telescopes.

In Sections 6, 7 and 8, we will discuss massive binary evolution in the context of WR + O binaries, long gamma-ray burst and gravitational wave observations.

3. STELLAR WIND MASS LOSS

Stellar wind mass loss is a very important parameter that has to be included in stellar evolution when dealing with massive stars. For example, at solar metallicity, a 15 $M_\odot$ star loses 2 to 3 $M_\odot$ during its entire life. In more extreme cases, for stars with masses around 100 $M_\odot$, the stellar wind will remove more than half of the stellar mass during its lifetime (Ekstrom et al. 2012).

During the main sequence phase, winds from massive stars are in general described with the radiation-driven wind theory (Lucy and Solomon 1970, Castor et al. 1975). This theory was improved over the years and various theoretical mass loss rates have been calculated (Kudritzki et al. 1989, Kudritzki and Puls 2000, Vink et al. 2000, 2001). However, computed mass loss rates seem to disagree by a factor 2-3 with the values obtained from observations (Najarro et al. 2011, Šurlan et al. 2013, Rauw et al. 2015). The mass loss rates of O-type stars with an initial mass larger than 30-40 $M_\odot$ are uncertain by at least a factor of two (Puls et al. 2008).

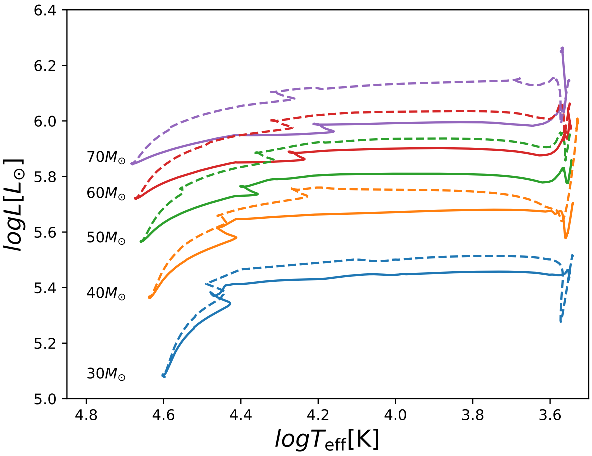

Fig. 2: Evolutionary tracks of single stars in range of 30 to 70 $M_\odot$ calculated with the MESA evolutionary code. Stellar wind mass loss is calculated according to Vink et al. (2001) (solid lines) and with scaling factor of 0.1 (dashed line).

Massive stars that are evolving in binaries are very likely to lose most of their hydrogen envelopes in a mass transfer process and become WR stars. Those helium core burning stars are characterized by strong stellar optically thick winds, whose origin and magnitude are also still not well understood but theoretical mass loss rates are given by a few authors (Grafener et al. 2002, Hamann et al. 1995, Hamann and Koesterke 1998, Moffat and Marchenko 1996).

In general, mass loss rates depend on the metallicity, but the most accurate scaling is not yet completely clear. The metallicity dependence has been estimated initially to be 0.4 (Abbott 1982), and then between 0.5 Kudritzki (2002) and 0.85 (Vink et al. 2001). Mokiem et al. (2007) found the empirical scaling deduced from observations of early B-type and O-type stars to be between 0.72 and 0.83.

Also, for the most massive main sequence O-type and WR stars, a dependence of the mass loss rate on the Eddington factor is established by a few authors (Vink et al. 2011, Grafener et al. 2011, Bestenlehner et al. 2014). This dependence is around Γ^2 for O-stars with $\Gamma < 0.70$, and around Γ^4 for WR stars with $\Gamma > 0.70$ and the Eddington factor is given as:

$$\Gamma = \kappa L/(4\pi cGM), \tag{4}$$

where κ is opacity, L is stellar luminosity, G is the gravitational constant and M is the stellar mass.

During the red supergiant phase, the mass-loss rates are even less well known. Observations exhibit a very strong scatter, with variations over more than 2 orders of magnitude at a given luminosity (Mauron and Josselin 2011, van Loon et al. 2005, Beasor and Davies 2016, Georgy 2017). Most of the stellar evolutionary codes use the RSG wind formalism proposed by de Jager et al. (1988). However, Vanbeveren et al. (2007) showed that in the luminosity interval $4 < \log(L/L_\odot) < 5.5$ this prescription may significantly underestimate the true mass loss rates.

This uncertainty of the stellar wind mass loss rates, for different evolutionary phases, has a major impact on the results of stellar evolutionary calculations of massive single and binary stars. Such a difference can significantly influence the evolution of massive stars, even more so if they are evolving in binary systems and are undergoing an additional mass loss, via mass transfer to the companion. It can cause different outcomes during the late evolution and after the supernova explosion.

In case of single stars, if mass loss rates are best described by the theoretical predictions, an explanation for so-called "red-supergiant problem" (Smartt et al. 2009) is yet to be found. In case that theoretical calculations are underestimating mass loss rates, stars evolve back toward the hot side of the Hertzsprung-Russell diagram (Meynet et al. 2015).

In the case of interacting binary stars, higher stellar wind mass loss rates would help the removal of the hydrogen envelope of the mass donor. In some cases of very extended stellar envelopes, high stellar wind mass loss rates leading to a removal of this envelope before mass transfer on a dynamical scale can take place. This would prevent the formation of a common envelope and spiraling-in to a very close binary or a merger. In all cases, the amount of material to be transfered from one star to another is smaller in case of higher stellar wind mass loss rates. This also influences orbital changes that happen mostly due to mass transfer episodes.

The possibility that the radiation and stellar wind momenta can remove part of the matter flowing from one towards another star during the mass transfer was investigated by Dessart et al. (2003). However, it was shown that those mechanisms can not be the explanation for a non-conservative mass transfer, even in case of very low mass transfer rates ($\approx 10^{-6}$ $M_\odot$/yr).

4. ROTATION AND MAGNETIC FIELDS

Rotation is an important process in stellar evolution that has been studied since early 20th century (Von Zeipel 1924, Eddington 1926). The influence of the centrifugal force in rotating models was investigated by Kippenhahn and Thomas (1970). Meynet and Maeder (1997) have modified the Kippenhahn and Thomas (1970) system of equations for the case of shellular rotation. Zahn (1977) researched synchronization between rotational and orbital motion in binary systems due to tidal spin-orbit coupling.

Single massive stars in the range of 10 - 20 $M_\odot$ have various rotational velocities from low to almost critical values (Vink et al. 2010). The more massive stars can lose a significant amount of angular momentum due to stellar winds, which leads to slower rotation (Meynet and Maeder 2000, Brott et al. 2011).

Rotation triggers an internal mixing that transports chemicals and angular momentum within a star. Since rotational mixing brings extra fuel into the stellar core, rotating stars develop larger convective cores compared to non-rotating stars. Also, rotation induces mixing and transport in regions outside the convective core by meridional circulation and shear instabilities. The result is a change of the chemical composition of mixing regions or even at the stellar surface layers.

In some extreme cases, the mixing during the main sequence is so strong that the star evolves quasi chemically homogeneously (Yoon et al. 2006, Szécsi et al. 2015). In that case the star becomes extremely hot and compact, becoming a possible progenitor for long soft gamma-ray bursts (de Mink and Mandel 2016).

The evolution of massive single stars can be significantly influenced by rotation (Heger et al. 2000, Meynet and Maeder 2000) and evolutionary models of rotating stars are available for many masses and metallicities. Effects of rotation can be even more important for binary evolution, since angular momentum is transfered together with material during the mass transfer process. Accretion, via a viscous disk or via ballistic impact, transports angular momentum, and evolutionary models show that this can lead to a significant spin-up and even critical rotation of the mass gaining star (Packet 1981, Langer et al. 2000, Yoon and Langer 2004).

The material being transferred from one star to another carries a certain angular momentum that will be transfered to the mass gaining star. If there is an accretion disk, the angular momentum of the transfered matter is assumed to be Keplerian. If there is direct impact accretion, the angular momentum is calculated by following a test particle moving through the first Lagrangian point. This angular momentum spins-up the top layers of the mass gaining star and is further transferred through the star due to a rotationally induced mixing processes (Heger and Langer 2000). Each time the secondary spins-up close to critical rotation, it starts losing more mass due to the influence of the centrifugal force. High mass loss decreases the accretion efficiency and removes angular momentum from the secondary star. The secondary star is also slowed down by the tidal interactions that try to synchronize it with the orbital motion.

Assumed that the specific angular momentum of the accreted matter corresponds to the Kepler rotation at the stellar equator, the mass gaining star will reach critical rotation when its initial mass is increased by about 5-10% (Packet 1981). The mass accretion can continue in this situation, as viscous processes may transport angular momentum through the star (Paczynski 1991). However, if the star is rotating very rapidly, its wind mass loss may dramatically increase (Langer 1998), which may result in a very inefficient mass transfer (Petrovic et al. 2005a,b).

Rotationally enhanced mass loss is given as :

$$\dot{M}/\dot{M}(v_{\rm rot}=0) = 1/(1-\Omega)^{\xi}, \tag{5}$$

with

$$\Omega = v_{\rm rot}/v_{\rm crit}, \tag{6}$$

$$v_{\rm crit}^2 = GM(1-\Gamma)/R, \tag{7}$$

where $\xi = 0.43$, Γ is the Eddington factor (Eq. 4), $v_{\rm rot}$ rotational velocity and $v_{\rm crit}$ critical rotational velocity (Langer 1998).

A detailed study of the effects of rotation on the evolution of the mass gainers in massive binaries was presented by Wellstein et al. (2001), Petrovic et al. (2005a), Petrovic et al. (2005b), Cantiello et al. (2007), Detmers et al. (2008), De Mink et al. (2009). Those evolutionary models include details of the mass and angular momentum transfer process, angular momentum transport through stellar interiors due to rotationally induced mixing processes, as well as spin-orbit coupling through tidal interaction in binaries.

Wellstein et al. (2001) investigated the influence of rotation processes in binary systems with initial masses in the range of 12 to 25 $M_\odot$ and mass ratios close to one, so the systems would evolve through stable mass transfer and avoid contact. They found that the accretion efficiency does not decrease significantly due to rotation for Case A mass transfer, but in Case B mass transfer efficiency can be significantly decreased and lead to rotation of the mass gainer near the critical velocity. Petrovic et al. (2005a) considered rotating models in the range of 40 - 60 $M_\odot$ with larger mass ratios and found that accretion can be significantly decreased during Case A mass transfer. The explanation for this is that the maximum mass transfer rate increases with the increase of the initial mass ratio. Further, if more mass and angular momentum is transferred to the mass gaining star, its rotational velocity increases more, as well as its mass loss. This results in a lower accretion efficiency during the mass transfer. de Mink et al. (2014) have shown that a combination of tidal interaction in the binary and wind mass loss can prevent a star from reaching critical rotational velocity and allow it to further accrete matter. In this case, part of the angular momentum is transferred to the orbit or lost in the stellar wind.

While it was shown that accretion spins-up the mass gainer in the process of mass transfer, this process is hindered by the tidal interactions that try to keep the rotation of the stellar components synchronized with the orbital motion (Petrovic et al. 2005a,b).

Another important parameter in massive binary evolution is the magnetic field. As shown by Spruit (2002) a dynamo can operate in the radiative zone of a differentially rotating star. The resulting magnetic field causes an efficient torque able to reduce the differential rotation and force the star to rotate uniformly. Heger et al. (2005) researched the effects of this process on massive star evolution and found that it decreases the effects of rotation on massive star evolution. Maeder and Meynet (2005) modeled the evolution of a 10 $M_\odot$ star with and without rotationally induced magnetic fields, and also their results indicated that the overall influence of rotation on stellar evolution becomes smaller when magnetic fields are included.

The increase of rotational velocity of the mass gainer in massive close binary systems and fast rotating massive stars that are possible progenitors of long gamma-ray bursts are further discussed in Section 7.

5. NUMERICAL STELLAR EVOLUTION CODES

Evolutionary calculations of massive close binaries have been done by many authors, for example, Paczynski (1967), Kippenhahn et al. (1967), van den Heuvel and Heise (1972), Vanbeveren et al. (1979), Vanbeveren (1982), de Loore and de Greve (1992), de Greve and de Loore (1992), Wellstein and Langer (1999), Wellstein et al. (2001), Petrovic et al. (2005a), Petrovic et al. (2005b), Cantiello et al. (2007), Eldridge et al. (2008), Detmers et al. (2008), De Mink et al. (2009), de Mink et al. (2014).

One-dimensional (1D) stellar evolution codes, used to model binary interactions, solve the four equations of stellar structure Kippenhahn and Weigert (1990). Such codes include a network of nuclear reactions, calculate the energy generation rate inside the stellar model, and the time evolution of the chemical structure of the star. They also can include parametrized rotational mixing and magnetic fields etc. Numerical codes adapted for binary stellar evolution additionally include mass transfer calculations, tidal interactions and the evolution of orbital parameters.

There are a few known stellar evolution codes used during the last decades for the modeling of binary stellar evolution. For example, the binary evolution code STERN (or Utrecht/Bonn Evolutionary Code), based on the original Kippenhahn code Heger and Langer (2000), Wellstein et al. (2001), Petrovic et al. (2005a,b), Yoon et al. (2010) includes mass transfer, tidal interactions, parametrized rotational mixing and magnetic fields. Another well known code is the Eggleton code (Eggleton 1972) and its more modern versions STARS. It includes mass transfer and tidal interactions, with the most modern version also including magnetic field generation. The Population synthesis Brussels code (Vanbeveren et al. 1998, De Donder and Vanbeveren 2004, Mennekens and Vanbeveren 2014) is stellar evolution code used for both detailed evolution and population synthesis. The BINSTAR code (Siess et al. 2013) includes also the physics of mass transfer in eccentric systems.

The newest widely used 'state-of-the-art' stellar evolution code is MESA - Modules for Experiments in Stellar Astrophysics (Paxton et al. 2011, 2013, 2015, 2018).

6. WR + O BINARY SYSTEMS

Wolf-Rayet stars are massive helium core burning stars which have evolved from main sequence O-type stars and lost most or all of their hydrogen-rich envelope during their evolution Chiosi and Maeder (1986), Maeder and Conti (1994). They are characterized with high effective temperatures, luminosity and stellar wind mass loss rate (Grafener et al. 2002). The stellar wind of Wolf-Rayet stars is optically thick, preventing a direct determination of radii of WR stars (Hamann et al. 1995, Moffat and Marchenko 1996). Beside strong stellar wind, the Roche lobe overflow in interacting binaries was identified as a possible physical process that can explain the removal of the hydrogen envelope Wellstein et al. (2001).

The surface composition of WR stars is dominated by helium. Spectra are also showing broad nitrogen, carbon and oxygen wind emission lines. Based on the presence of those lines, WR stars are classified in three subtypes: WN, WC and WO stars. Based on the strength of the nitrogen and carbon lines, all WR stars are further classified from WN2 to WN9 and WC2 to WC9 (Smith et al. 1996). Wolf-Rayet stars with nitrogen lines are extra divided into early type, without hydrogen (WNE) and late type with some hydrogen still present (WNL) (Vanbeveren and Conti 1980). Hamann et al. (2006) indicated that the WNL population is dominated by single stars, which lose hydrogen from their envelopes only via stellar wind.

Models of massive close binary evolution were presented by various authors. General ideas about the formation of WR+O binary systems were given by Paczynski (1967), Kippenhahn et al. (1967), van den Heuvel and Heise (1972). Some years later Vanbeveren et al. (1979) presented models of massive close binaries evolving via Case B mass transfer with various assumptions for mass and angular momentum loss from the binary system. Vanbeveren (1982) found that most of the WR primaries must have evolved from stars initially more massive than 40 $M_\odot$ via highly non-conservative ($\beta < 0.3$) Case B mass transfer in order to fit the observations.

The calculations of massive Case B binary systems with initial masses from 9 $M_\odot$ to 40 $M_\odot$ with a mass ratio from 0.6 to 0.9 were presented by de Loore and de Greve (1992). They made non-conservative models assuming that the accretion efficiency is $\beta = 0.5$, so half of the transfered mass leaves the binary system.

Wellstein and Langer (1999) and Wellstein et al. (2001) modeled massive binary systems with a mass range of 12 to 60 $M_\odot$. Wellstein et al. (2001) presented rotating models for binary systems with initial masses $\approx$ 15 $M_\odot$, both for Case A and Case B and an initial mass ratio $q1$.

Petrovic et al. (2005a) have presented evolutionary models in the mass range of 40 to 75 $M_\odot$ to model progenitors of three selected WR+O systems: HD186943 (WN3), HD90657 (WN5) and GP Cep (WN6/WCE), with mass ratios $q = M_{\rm WR}/M_{\rm O} \approx 0.5$ and orbital periods between 6 and 10 days. Observed WR masses are in the range of about 10 - 15 $M_\odot$. Their models with accretion efficiency of 10% reproduce the observations the best. They also present highly non-conservative rotating models — in which the accretion efficiency is not an a priori chosen parameter, but the result of a modeled physical process. The modeled data are shown in Fig. 3.

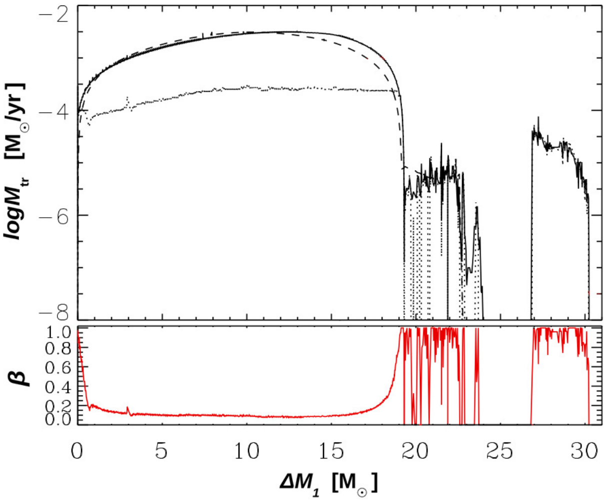

Fig. 3: The upper panel shows the mass transfer (solid line) and accretion rate (dotted line) of a rotating binary system 56 $M_\odot$ + 33 $M_\odot$ with the initial orbital period of 6 days modeled with the STERN evolutionary code. The dashed line represents the mass transfer rate in a non-rotating binary system with the same initial masses and orbital period. The lower panel shows the accretion efficiency of the secondary in rotating system (β).

It should also be noted that not many WR + O binary systems have been observed. About 20 with known masses of the components are listed in the catalog of van der Hucht (2001). Listed WR masses span a very large range from only a couple solar masses (HD94546 an HD320102) to over 50 $M_\odot$ (HD311884). Three WR stars have been observed in binary systems with compact objects (Crowther et al. 2010).

Massive binary systems consisting of two O-type stars with too different masses would not be able to produce a WR + O binary, because the mass transfer would not be stable and the evolution would go via the common envelope channel. If the initial mass ratio of O stars is too close to unity, the mass transfer would produce a binary system where the post-RLOF O star is more massive than the WR star. So, the initial mass ratio has to be somewhere in between, far enough from unity to produce the observed masses, but also not too far to cause evolution via contact (Petrovic et al. 2005a).

The understanding of the WR + O progenitor evolution is important for the understanding of gamma-ray bursts (GRBs) and, since recent observations by LIGO and Virgo detectors, also the gravitational wave emission. According to the collapsar model (MacFadyen et al. 2001), long gamma-ray bursts originate in fast rotating hydrogen free WR stars which are massive enough to form a black hole at the end of their evolution and explode as a supernova (Type Ic) (Woosley 1993a, Woosley et al. 1995). This theory is in agreement with GRB afterglow observations reported by Hjorth et al. (2003).

WR + O binary systems evolve via two supernova explosions to create double compact binaries consisting of two black holes, two neutron stars or one of each. Mergers in such systems have been recently identified as sources of gravitational wave emission. (Abbott et al. 2019).

7. SUPERNOVAE, COLLAPSARS AND GAMMA-RAY BURSTS

Iron core collapse supernovae are classified as Type I or Type II, depending on whether they have hydrogen lines in the spectra (Type II) or show an absence of hydrogen lines (Type I). Type Ib and Type Ic supernovae are related to massive star explosions in binary systems. Both of those supernovae types lack hydrogen in their spectra. The Type Ib supernovae show helium lines, while Type Ic lack both hydrogen and helium lines. This means that Type Ib are related to core collapsing massive stars that lost their hydrogen envelope and Type Ic with core collapsing massive stars that lost both hydrogen and helium rich layers.

There has been a lot of evidence that collapsing massive stars are the progenitors of long gamma-ray bursts (GRBs) (Woosley and Bloom 2006, Gehrels et al. 2009). Supernova explosions of massive fast rotating stars might be connected with the creation of a collapsar (Woosley 1993a): a massive - 35-40 $M_\odot$ (Fryer 1999) rotating star whose core collapses to form a black hole accreting the rest of the star in a very short time (Woosley 1993b, MacFadyen and Woosley 1999). There have been several observations of GRBs associated with supernovae Type Ic (Hjorth et al. 2003). Also, it has been shown that afterglows of those supernovae show signatures of the circumstellar medium being shaped by a massive progenitor star (van Marle et al. 2005).

The question is which evolutionary channel can produce fast spinning presupernova stars? Massive single stars have high stellar wind mass loss rate and in this way they lose angular momentum, both during the main sequence and WR phase. On the other hand, massive stars in binary systems might be spun-up by an accretion process that carries not only matter, but also angular momentum to the gainer. Most long gamma-ray bursts seem to occur at low metallicity (Fruchter et al. 2006), which is in agreement with the stellar wind mass loss dependence on metallicity that we have mentioned in Section 3.

The models (Woosley 1993b, MacFadyen and Woosley 1999) showed that if a star has enough angular momentum in the equator ($3\times10^{16}\mathrm{cm}^2/\mathrm{s}$), an accretion disk will be formed around the black hole. Extremely fast accretion of the rest of the star at accretion rates up to 0.1 - 1 $M_\odot$/s in the newly formed black hole releases large amounts of energy ($\approx 10^{51}$ erg/s). The jet, coming from heated gas expanding with relativistic speed at the poles, and the shock wave, can result in a GRB and a Type Ib/c supernova event.

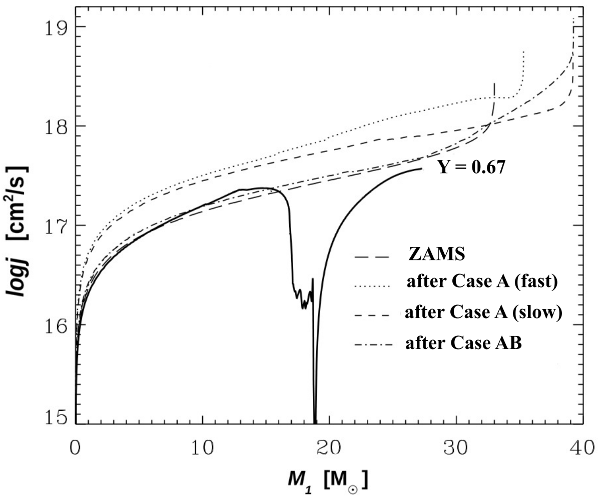

Fig. 4: Specific angular momentum profiles of the secondary star in a binary system 56 $M_\odot$ + 33 $M_\odot$ with the iitial orbital period of 6 days calculated with the STERN evolutionary code. The long-dashed line shows the profile on the ZAMS (Zero Age Main Sequence), dotted line after the fast phase of Case A, dashed line after the slow phase of Case A, dash-dotted line after Case AB and solid line during the helium core burning, after which insignificant angular momentum loss is expected.

Is it possible that a single star can be the progenitor of such an event? In case of extreme stellar wind mass loss during the WR phase, it may happen that a star loses its hydrogen envelope, but can its core rotate so fast as before the supernova explosion? To investigate this (Heger et al. 2000) have calculated models of a 25 $M_\odot$ star that could form a black hole by a fallback. They have found that such a star would have enough angular momentum to produce a collapsar, but it was not clear if it can shed its hydrogen envelope. The core is able to keep rotating fast despite the stellar wind mass loss, because the so-called μ-gradients represent a barrier for rotational mixing and transport of angular momentum, so the core does not lose large amount of angular momentum during the evolution, even if the envelope loses a lot of matter via stellar winds (Heger and Langer 2000). The influence of a magnetic field that can influence the transport of angular momentum within a star (Spruit and Phinney 1998), was not considered.

Heger et al. (2004) included the angular momentum transport by magnetic torques, using the dynamo model presented by Spruit (2002). The magnetic torques keep the rotation of the stellar core and the stellar envelope more synchronized. The envelope slows down due to stellar wind mass loss and the resulting angular momentum in the core is one to two orders of magnitude less than what is required by the collapsar model of GRB production. However, it is still possible that the dynamo model by Spruit (2002) overestimates the influence of magnetic fields.

In the case of binary systems, before the mass transfer, tidal spin-orbit coupling synchronizes the rotation of both stars with the orbital motion, which leads to a specific angular momentum which is by factor of 3 to 5 smaller than in a corresponding single star. However, Wellstein et al. (2001) and Petrovic et al. (2005b) showed previously that during the mass transfer phase in a binary system, the secondary (accreting) star can spin up close to the critical rotation, i.e. the surface layers of this star can gain significant angular momentum. This angular momentum can be transported inwards and increase the rotation velocity of the stellar core. Stars with a mass of about 40 $M_\odot$ are able to retain enough angular momentum in their cores to produce GRBs.

Petrovic et al. (2005b) also considered massive binary models with a magnetic field Spruit (2002). In this case, the core spin-up due to the accretion is stronger. It leads to a core spin rate which is by factor of 2 to 3 above that of a ZAMS star of comparable mass. However, the magnetic core-envelope coupling reduces the specific core angular momentum by almost a factor of 100 by the time the star has started the core helium burning. Its final core angular momentum will be far too small to produce a GRB.

Detmers et al. (2008) have investigated a possible spin-up of a WR star in a later evolutionary stage. However, the results have shown that the tidal interaction of a Wolf-Rayet star with a compact object in a binary system can not spin up the Wolf-Rayet star enough to produce a collapsar at Solar metallicity. On the other hand (Fryer and Heger 2005, Podsiadlowski et al. 2010, Tout et al. 2011) proposed various scenarios to spin up WR stars in close binary systems for high metallicity.

The question of the exact progenitor evolution of long gamma-ray bursts stays open. It was shown that the accretion does add significant angular momentum to the stellar core of the gainer. However, it is not clear how the angular momentum can be preserved until the supernova explosion, since the stellar wind mass loss, magnetic torques and tidal interactions are slowing down the stellar rotation. There is a possibility that accretion on the WR star near its end might play a role or late stellar merger may lead to an efficient core spin up.

8. GRAVITATIONAL WAVE SOURCES

The observations of gravitational waves in the last few years indicated that those signals are connected with mergers of compact objects in massive binary systems. The first signal (GW150914) was interpreted as two massive black holes of about 36 $M_\odot$ and 29 $M_\odot$ (Abbott et al. 2016c). The second signal was associated with the merger of slightly less massive black holes, about 14 $M_\odot$ and 7.5 $M_\odot$ (Abbott et al. 2016a). The first detection of a gravitational wave signal related to a merger of neutron stars was reported in 2017 (Abbott et al. 2017). In total, LIGO and Virgo detectors observed so far about 20 gravitational wave events, 18 related to mergers of binary black holes with masses in the range of about 7 $M_\odot$ to 85 $M_\odot$ and two events related to neutron star mergers with masses of about 1.5 $M_\odot$ (Abbott et al. 2019, 2020).

Double compact objects associated with gravitational wave emission, consisting of black holes and neutron stars, are relics of massive binary star evolution. Such binary systems start as double O-type stars and evolve through multiple interactions in their lifetimes, transferring matter and angular momentum from one to another. Those systems evolve through a Wolf-Rayet + O phase, a X-ray binary phase, likely CE episode(s) and survive two supernova explosions.

After a WR+O phase that was discussed in detail in Section 6, the primary star will evolve to a supernova explosion and the first compact object will be formed in a binary. Depending on the force of the SN kick, the orbital period will be more or less affected and in some cases the binary system will be disrupted. If a binary system stays bound, the secondary star evolves further into a red giant with a hydrogen burning envelope. This will cause a mass transfer to the compact object and the system will be likely observable as an X-ray binary. Eventually, the secondary will also undergo a supernova explosion (Ib/c) and the second compact object will be formed. There is also a probability that the system becomes disrupted in this second supernova event. If the binary stays bound, the compact objects will eventually merge.

Many authors have published results on the physics of double compact objects formation, for example Bisnovatyi-Kogan and Kombert (1974), Wheeler et al. (1974), Flannery and van den Heuvel (1975) and more recent Ivanova et al. (2003), Dewi and Pols (2003), Podsiadlowski et al. (2004), Dewi et al. (2005), Belczynski et al. (2008), Tauris et al. (2015) and Tauris et al. (2017).

Considering models of gravitational wave progenitors, the work by Kruckow et al. (2018) should be mentioned. They have modeled the evolution of binary systems using the population synthesis method and included the mass loss, mass transfer and accretion, common envelopes, and supernova kick estimates. The resulting compact objects are determined depending on the mass of the progenitor carbon-oxygen core. Neutron stars are the result of an iron-core collapse supernova if a carbon-oxygen core has a mass in the range of 1.435 to 6.5 $M_\odot$ (Tauris et al. 2015). Black holes are formed if the carbon-oxygen core mass is above 6.5 $M_\odot$.

They have found that the double neutron star systems originate from binaries where both components are initially less massive than about 30 $M_\odot$. To form double black hole binaries, it is necessary to have initial stellar masses above this value. In the lower metallicity regime, more black hole binaries will be formed, because of the lower stellar wind mass loss rate. Mixed NS-BH binaries are formed only from binary systems with initial masses between 30 and 40 $M_\odot$ and an initial mass ratio near one.

Fig. 1 shows an example of the mass transfer rate in binary systems with initial stellar components around 30 $M_\odot$, so exactly in the transition parameter space from neutron stars to the black hole formation.

As we already mentioned, those systems evolve via the Case A, Case AB and Case ABB mass transfer to the iron core formation of the primary star. The MESA evolutionary code is used for those calculations.

The masses of carbon-oxygen cores in binary systems 30 $M_\odot$ + 27 $M_\odot$ and 32 $M_\odot$ + 28.8 $M_\odot$ are under the 6.5 $M_\odot$ limit (5.41 and 6.04 $M_\odot$ respectively) and the remnant of the supernova explosion is a neutron star. The primary in the binary 34 $M_\odot$ + 30.6 $M_\odot$ develops a carbon-oxygen core of 6.79 $M_\odot$ and a black hole will be the result of the SN explosion. In both systems, the secondary will further evolve via a supernova explosion into a compact object. If such systems are not disrupted by either of the supernova explosions, they become double compact objects, that later during merger emit gravitational waves.

9. SUMMARY

The evolution of massive binary systems relates to many exciting astrophysical phenomena. However, there are still many uncertainties and open questions.

First, stellar wind mass loss calculations are still to be improved, especially for red supergiants and Wolf-Rayet stars. Mass loss via stellar wind removes a large amount of matter and angular momentum in case of massive stars and it directly influences the size of the final stellar core and its rotational velocity. In this way, the stellar wind mass loss can determine whether the final core collapses into a neutron star or a black hole and if it has enough angular momentum to possibly produce a gamma-ray burst together with a supernova explosion. In other words, the initial-final mass relation for massive stars still has to be precisely established, as well as the connection between the initial and the final angular momentum profiles in binary stars.

Further, there is an open question about the efficiency of mass transfer in massive binary systems. Also, it is not fully known what physical processes can contribute to interactions being non-conservative. To recreate the observed WR + O systems accretion as low as 10% is needed. Stellar rotation was identified as an important parameter that can influence the accretion efficiency in massive binary systems. Stars rotating with a velocity near the critical value have extremely high mass loss rates and, in this way, the mass transfer is being highly non-conservative. Besides this, the rotation is also related to the appearance of long gamma-ray bursts, as it is necessary that a stellar core has a certain angular momentum to create a collapsar – a collapsing black hole that is accreting the rest of the star.

The influence of magnetic fields on massive binary evolution is still not fully understood. Current models of magnetic dynamo do not support models of long gamma-ray bursts created in massive binaries. Magnetic torque decreases angular momentum of the stellar core, synchronizing it with the stellar envelope that is slowed down by the tidal interactions in a binary system.

Finally, the recent detection of gravitational waves by the LIGO and Virgo detectores have opened a new and exciting chapter in the massive binary evolution research. Evolving from double O-type binaries and going through a WR + O phase, massive binaries become double compact objects. Mergers between components in those systems, neutron stars and black holes, give rise to the emission of gravitational waves. A detailed understanding of progenitor evolution of double compact binaries is still to come. The influence of metallicity, stellar wind, rotation, accretion efficiency etc. in detailed evolutionary models, as well as the effects of the common envelope phase and supernova kick in the evolution of those objects, is still to be discovered.

Acknowledgements – The author acknowledges the financial support of the Ministry of Education, Science and Technological Development of the Republic of Serbia through contract No. 451-03-68/2020-14/200002.

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ЕВОЛУЦИЈА МАСИВНИХ ДВОЈНИХ СИСТЕМА

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УДК 524.387–54
Прегледни рад по позиву

Еволуција масивних звезда у блиским двојним системима се значајно разликује од еволуције усамљених звезда, највише због низа интеракција између чланова двојног система. Масивни двојни системи су повезани са разним интересантним астрофизичким феноменима. Пример су Wolf-Rayet двојни системи, тип Ib/c експлозија супернових и гама бљескови. Такође, у новијим посматрањима LIGO и Virgo детектора, гравитациони таласи су асоцирани са сударима компактних објеката у двојним системима. Ови компактни објекти, неутронске звезде и црне рупе, су резултат еволуције масивних двојних система. Еволуциони модели масивних двојних система су представљени од стране многих аутора, али су ипак многи аспекти еволуције и даље непознати. У овом раду је дат преглед основа еволуције масивних блиских двојних система и дискусија параметара као што су ротација, магнетно поље, губитак масе преко звезданог ветра и ефикасност акреције у току трансфера масе. Представљен је и опширан преглед лературе на тему масивних двојних система, у светлу узбудљивих посматрања повезаних са овим објектима.