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LAUREA TRIENNALE IN ASTRONOMIA

Evolutionary channels of binary black holes: the impact of common envelope

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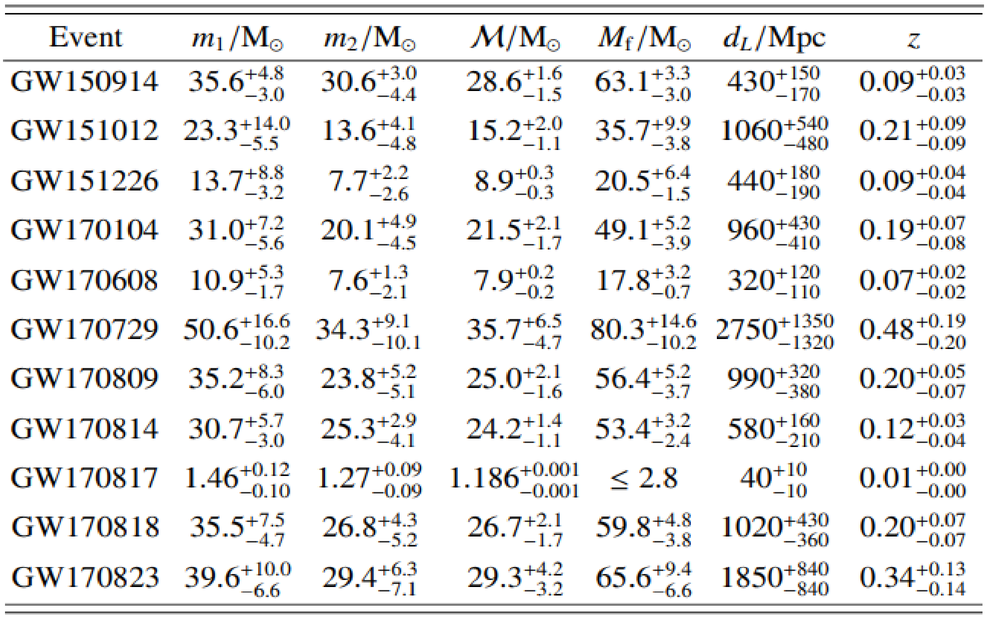
Abstract

With the first detection of gravitational waves by the LIGO interferometers in 2015 we had the observational proof that binary black holes exist and can merge within a Hubble time. Since then, many efforts have been made to study the formation channels of binary black holes. In this Thesis I have highlighted the most important results obtained in this field: I have reviewed the main processes driving mass transfer in stellar binaries and the main theoretical models to estimate the mass of compact remnants in binary systems. In particular, I have focused on the common envelope phase, discussing the most important aspects and the main open issues of this process. In this framework, I have analyzed a population-synthesis simulation of two isolated binary systems. Both systems become binary black holes and merge within a Hubble time, but only one of them undergoes a phase of common envelope. I've discussed the main differences between the two systems in the evolution of physical parameters (stellar masses, orbital separation and orbital eccentricity) that play a key role in our understanding of the formation of black hole binaries.

Introduction

On September 14 2015, a hundred years after Einstein's prediction, the LIGO interferometers captured a gravitational wave signal (GW150914) from two merging black holes, opening the era of Gravitational Waves Astrophysics. Eleven signals have been reported so far by the three interferometers: the two LIGO detectors in the United States and Virgo (joining on August 2017) in Italy. Ten of these signal are caused by two merging black holes, one of them is caused by two merging neutron stars (see Fig.1).Astrophysicists have learned several revolutionary concepts about black holes from gravitational waves detections. First, even though the formation of binary black holes was predicted a long time ago, we had no observational proof of this before September 2015: GW150914 has confirmed that binary black holes exist. Second, gravitational waves detections show that some binary black holes are able to merge within a Hubble time. We know from stellar evolution that black holes can originate from massive, relatively metal poor stars, but, on the other hand, the formation channels of merging black hole binaries are still an open question. In this thesis i will highlight the main results and the main open issues about the evolution channels of binary black holes, focusing on the impact of the common envelope process during the evolution of a binary system composed of two massive stars. Then, I will analyze two binary systems simulated through a population-synthesis code. Both systems evolve into binary black holes and merge within a Hubble time.However, one of the two systems goes through a phase of common envelope, while the other does not. The aim of this simulation is to highlight the main differences in physical parameters such as the total and the core-mass of the star, the eccentricity of the orbit and the separation between the two stars in the two different evolution processes.



Event	$m_1/\mathrm{M}_\odot$	$m_2/\mathrm{M}_\odot$	$\mathcal{M}/\mathrm{M}_\odot$	$M_\mathrm{f}/\mathrm{M}_\odot$	d_L/Mpc	z
GW150914	$35.6^{+4.8}_{-3.0}$	$30.6^{+3.0}_{-4.4}$	$28.6^{+1.6}_{-1.5}$	$63.1^{+3.3}_{-3.0}$	430^{+150}_{-170}	$0.09^{+0.03}_{-0.03}$
GW151012	$23.3^{+14.0}_{-5.5}$	$13.6^{+4.1}_{-4.8}$	$15.2^{+2.0}_{-1.1}$	$35.7^{+9.9}_{-3.8}$	1060^{+540}_{-480}	$0.21^{+0.09}_{-0.09}$
GW151226	$13.7^{+8.8}_{-3.2}$	$7.7^{+2.2}_{-2.6}$	$8.9^{+0.3}_{-0.3}$	$20.5^{+6.4}_{-1.5}$	440^{+180}_{-190}	$0.09^{+0.04}_{-0.04}$
GW170104	$31.0^{+7.2}_{-5.6}$	$20.1^{+4.9}_{-4.5}$	$21.5^{+2.1}_{-1.7}$	$49.1^{+5.2}_{-3.9}$	960^{+430}_{-410}	$0.19^{+0.07}_{-0.08}$
GW170608	$10.9^{+5.3}_{-1.7}$	$7.6^{+1.3}_{-2.1}$	$7.9^{+0.2}_{-0.2}$	$17.8^{+3.2}_{-0.7}$	320^{+120}_{-110}	$0.07^{+0.02}_{-0.02}$
GW170729	$50.6^{+16.6}_{-10.2}$	$34.3^{+9.1}_{-10.1}$	$35.7^{+6.5}_{-4.7}$	$80.3^{+14.6}_{-10.2}$	2750^{+1350}_{-1320}	$0.48^{+0.19}_{-0.20}$
GW170809	$35.2^{+8.3}_{-6.0}$	$23.8^{+5.2}_{-5.1}$	$25.0^{+2.1}_{-1.6}$	$56.4^{+5.2}_{-3.7}$	990^{+320}_{-380}	$0.20^{+0.05}_{-0.07}$
GW170814	$30.7^{+5.7}_{-3.0}$	$25.3^{+2.9}_{-4.1}$	$24.2^{+1.4}_{-1.1}$	$53.4^{+3.2}_{-2.4}$	580^{+160}_{-210}	$0.12^{+0.03}_{-0.04}$
GW170817	$1.46^{+0.12}_{-0.10}$	$1.27^{+0.09}_{-0.09}$	$1.186^{+0.001}_{-0.001}$	≤ 2.8	40^{+10}_{-10}	$0.01^{+0.00}_{-0.00}$
GW170818	$35.5^{+7.5}_{-4.7}$	$26.8^{+4.3}_{-5.2}$	$26.7^{+2.1}_{-1.7}$	$59.8^{+4.8}_{-3.8}$	1020^{+430}_{-360}	$0.20^{+0.07}_{-0.07}$
GW170823	$39.6^{+10.0}_{-6.6}$	$29.4^{+6.3}_{-7.1}$	$29.3^{+4.2}_{-3.2}$	$65.6^{+9.4}_{-6.6}$	1850^{+840}_{-840}	$0.34^{+0.13}_{-0.14}$

Figura 1: The eleven gravitational waves signals revealed by the LIGO-Virgo collaboration (GW170817 is the neutron stars merge). The first two columns shows the initial mass of each compact object, M is the chirp mass, M$_f$ the final mass of the system, d$_L$ the luminosity distance of the source and z its Redshift. [From Abbot et al. 2018$^{(1)}$]

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Capitolo 1

The formation of compact remnants

Black holes and neutron stars are expected to form from massive ($>8\mathrm{M}_{\odot}$) stars. The mass function of black holes is highly uncertain, because it may be affected by a number of barely understood processes. In particular, stellar winds and supernova explosions both play an important role on the formation of the compact remnants

1.1 Stellar winds

Stellar winds are outflows of gas from the atmosphere of a star. In cold stars such as red giants and asymptotic giant branch stars, they are mainly induced by radiation pressure on dust, which forms in the cold outer layers.In massive hot stars (O and B main sequence stars, luminous blue variables and Wolf-Rayet stars), stellar winds are powered by the coupling between the momentum of photons and that of metal ions present in the stellar photo sphere. A large number of strong and weak resonant metal lines are responsible for this coupling (line-driven stellar winds, see Wink et al 2001(5)). Understanding stellar wind is tremendously important for the study of compact object, because mass loss determines the pre-supernova mass of a star (both its total mass and its core mass), which affects the outcome of a Supernova explosion. In a simplified approach we can assume that in massive stars the mass loss depends on the metallicity of the star (Z) as $\dot{m} \propto \mathrm{Z}^{\alpha}$ (where $\alpha \approx$ 0.5 - 1 depending on the model). Simulations tells us for example that if we assume $\mathrm{Z}_{\odot}$=0.002, a solar-metallicity star with $90_{\odot}$ has lost more than 2/3 of the initial mass by the end of its life, while a star with the same mass but

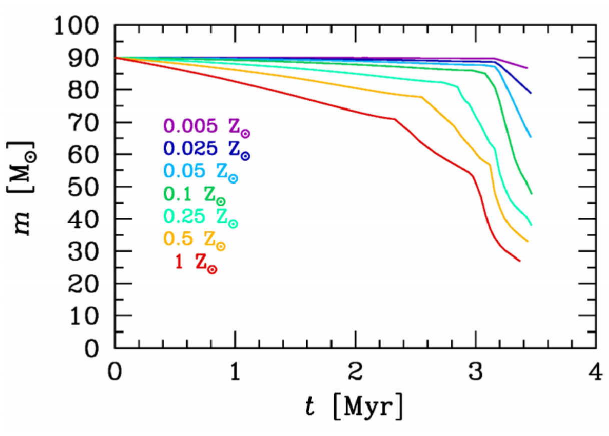

Figura 1.1: Evolution of stellar mass as a function of time for a star with $m_{ZAMS} = 90 M_{\odot}$ and seven different metallicities, ranging from 0.005 Z⊙ up to Z⊙ (we assumed Z⊙= 0.02).[From Mapelli, 2018 (2)]

with Z=0.005$Z_{\odot}$ has retained almost his initial mass (see Fig 1.1). Other aspects of massive star evolution affect the pre-Supernova mass of a Star. For example, surface magnetic fields appear to strongly quench stellar winds by magnetic confinement.Finally, the effect of rotation enhances the mass loss because it increases the stellar luminosity, on the other hand rotation induces chemical mixing, which leads to the formation of larger Helium and Carbon-Oxygen cores.

1.2 Supernova explosions

The mechanism triggering the iron-core collapse Supernovae are still highly uncertain. The basic framework and open issues are the following.As the mass of the central degenerate core reaches the Chandrasekhar mass $M_Ch \approx 1.44 M_{\odot}$, the degeneracy pressure of relativistic electrons becomes insufficient to support it against collapse. Moreover electrons are increasingly removed, because protons capture them producing neutrons and neutrinos. This takes the core into a new state where the matter is essentially composed of neutrons which support the cores against collapse by their degeneracy pressure. To reach this new equilibrium the core collapses from a radius of few thousand km down to a radius of few ten km in less than a second liberating W $\approx 5 \times 10^{53}$ erg of gravitational energy. The main problem is to explain how this gravitational energy can be (at least partially transferred) to the stellar envelope triggering the Supernova explosion. The most commonly investigated mechanism is the convective Supernova engine. According to this model, the collapsing core drives a bounce shock. For the Supernova explosion to occur, this shock must reverse the supersonic in-fall of matter from the outer layers of the star. Most of the energy of the shock consists in a flux of neutrinos.As soon as the neutrinos are free to leak out (because the shock has become diffuse enough), their energy is lost and the shock stalls. The Supernova occurs only if the shock is revived by some mechanism. In the convective SN scenario, the region between the proto-neutron star surface and the shock stalling radius can become convectively unstable (e.g because of Rayleigh-Taylor instability). Such convective instability can convert the energy leaking out of the proto-neutron star in the form of neutrinos to kinetic energy pushing the convective region outward. If the convective region overcomes the ram pressure of the infalling material, the shock is revived and the explosion is launched. If not, the SN fails.

1.3 The mass of the compact remnants

The previous sections suggest that our knowledge of the compact remnant mass is hampered by severe uncertainties,connected with both stellar winds and core-collapse Supernovae. However we can draw the following considerations. If the the zero-age main sequence (ZAMS) mass of a star is large $\mathrm{m}_{\mathrm{ZAMS}} \geq 30\ \mathrm{M}_{\odot}$, then the amount of mass lost by stellar winds is the main effect wich determines the mass of the compact remnant. At low metallicity($0.1\mathrm{Z}_{\odot}$) mass loss by stellar winds its not particularly large. Thus, the final mass m_{fin} and the Carbon-Oxygen mass m_{CO} of the star may be sufficiently large to avoid a core collapse. At high metallicity($\approx\mathrm{Z}_{\odot}$) mass loss by stellar winds is particularly efficient and may lead to a small m_{fin} and m_{CO}: the star is expected to undergo a core collapse SN and to leave a relatively small remnant. If the ZAMS mass of a star is relatively low ($7<\mathrm{m}_{ZAMS}<30\mathrm{M}_{\odot}$) then stellar winds are not important regardless of the metallicity. In this case, the details of the SN explosion are crucial to determine the final mass of the remnant.

1.4 Natal kicks

Compact object are expected to receive a natal kick from the parent SN explosion, because of asymmetries in the neutrino flux and/or in the ejecta. The natal kick has a crucial effect on the evolution of a black hole binary because it can either unbind the binary or change its orbital properties.

For example, a natal kick can increase the orbital eccentricity or misalign the spins of the two member of the binary. Unfortunately, it is extremely difficult to quantify natal kicks from SN simulations and measurements of natal kicks are scanty, especially for black holes, so this process remains quite uncertain

Capitolo 2

Binaries of stellar black holes

If the binary system is sufficiently wide (detached binary) for its entire evolution the two massive stars become a double black hole binary and the mass of each black hole will be the same as if its progenitor star was a single star. If the binary is close enough, though, it will evolve through several processes which might significantly change its final fate.

2.1 Mass transfer

If two stars exchange matter to each other, it means they undergo a mass transfer episode. This process obviously changes the mass of the two stars in a binary, and thus the final mass of the compact remnants of such stars, but also the orbital properties of the binary. If mass transfer is non conservative (which is the most realistic case in both mass transfer by stellar winds and Roche lobe overflow), it leads to an angular momentum loss, which in turn affects the semi major axis.

2.1.1 Mass transfer driven by stellar winds

When a massive star loses mass by stellar winds, its companion might be able to capture some of this mass. This will depend on the amount of mass which is lost and on the relative velocity of the wind with respect to the companion star. The mean mass accreition rate by stellar winds can be described, according to Hurley et al.(2002)$^{(6)}$, as

$$\dot{m}_2 = \frac{1}{\sqrt{1-e^2}}(\frac{Gm_2}{v_w^2})^2 \frac{\alpha_w}{2a^2} \frac{1}{[1+(v_{orb}/v_w)^2]^{3/2}} \dot{m}_1$$

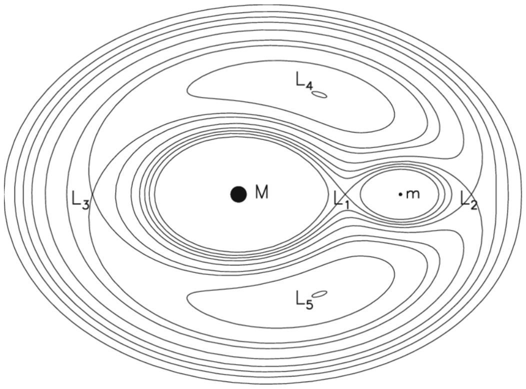

Figura 2.1: Equipotential surfaces and Lagrangian points of a binary system

where e is the binary eccentricity, G is the gravitational constant, m_2 is the mass of the accreting star, v_w is the velocity of the wind, $\alpha_w \approx 3/2$ is an efficiency constant, a is the semi major axis of the binary, $v_{orb} = \sqrt{G(m_1+m_2)/a}$ is the orbital velocity of the binary(m_1 is the mass of the donor) and $\dot{m}_1$(we assume >0) is the mass loss rate by the donor.Since $\dot{m}_1$ is usually quite low ($<10^{-3} M_{\odot} yr^{-1}$) and v_w is usually quite high (>1000 km s^{-1} for a line driven wind) with respect to the orbital velocity, this kind of mass transfer is usually rather inefficient.

2.1.2 Mass transfer by Roche-lobe filling

Mass transfer via Roche lobe overflow is usually more efficient. The Roche lobe of a star in a binary system is the maximum equipotential surface around the star within which matter is bound to the star. While the exact shape of the Roche lobe should be calculated numerically,a widely used approximated formula is

$$r_{L,1} = a\frac{0.49q^{2/3}}{0.6q^{2/3}+\ln(1+q^{1/3})}$$

where a is the semi major axis of the binary and q=m_1/m_2 (m_1 and m_2 are the masses of the two stars in the binary). This formula describes the Roche lobe of star with mass m_1, while the corresponding Roche lobe of star with mass $m_2(r_{L,2})$ is obtained by swapping the indexes. The Roche lobes of the two stars in a binary are thus connected by the L1 Lagrangian point (see Fig. 2.1). Since the Roche lobes are equipotential surfaces, matter orbiting at or beyond the Roche lobe can flow freely from one star to the other. We say that a star overfills its Roche lobe when its radius is larger than the Roche lobe.If a star overfills its Roche lobe, a part of its mass flows toward the companion star which can accrete (a part of) it. The former and the latter are thus called donor and accretor star, respectively. An important point about Roche lobe overflow is to estimate whether it is (un)stable and on which timescale. A commonly used approach consists in comparing the following quantities

$$\zeta_{ad} = \left(\frac{d\ln R_1}{d\ln m_1}\right)_{ad}$$

$$\zeta_{th} = \left(\frac{d\ln R_1}{d\ln m_1}\right)_{th}$$

$$\zeta_{L} = \left(\frac{d\ln r_{L,1}}{d\ln m_1}\right)$$

where ζ_{ad} is the change of radius of the donor (induced by the mass loss) needed to adiabatically adjust the star to a new hydrostatic equilibrium, ζ_{th} is the change of the radius of the donor (induced by the mass loss) needed to adjust the star to a new thermal equilibrium, and ζ_L is the change of the Roche lobe of the donor (induced by the mass loss). If $\zeta_L > \zeta_{ad}$, then the star expands faster than the Roche lobe (on conservative mass transfer) and mass transfer is dynamically unstable. If $\zeta_{ad} > \zeta_L > \zeta_{th}$ then mass transfer becomes unstable over a Kelvin-Helmholtz timescale. Finally, if min(ζ_{ad},ζ_{th}) $> \zeta_L$, mass transfer is stable until nuclear evolution causes a further expansion (or contraction) of the radius. If mass transfer is dynamically unstable $\zeta_L>\zeta_{ad}$ or both stars overfill their Roche lobe, then the binary is expected to merge-if the donor lacks a steep density gradient between the core and the envelope-,or to enter common envelope (CE)-if the donor has a clear distinction between core and envelope.

Capitolo 3

Common Envelope

Let us illustrate schematically the most important aspects of the 'isolated binary formation scenario', i.e the model which predicts the formation of merging black holes through the evolution of isolated binaries. For isolated binaries we mean stellar binary systems which are not perturbed by other stars or compact objects.
Initially,two gravitationally bound massive stars in a isolated binary system are both on the main sequence (MS). When the most massive one leaves the MS (i.e. when Hydrogen burning in the core is over, which happens usually of few Myr form massive stars with m_{ZAMS}>30M$\odot$), its radius starts inflating and can grow by a factor of hundreds. The most massive star becomes a giant star with Helium core and large Hydrogen envelope. If its radius equals the Roche lobe the system starts a stable mass transfer episode. Some mass is lost by the system, some is transferred to the companion. After several additional evolutionary stages, the primary collapses to a BH (a direct collapse is preferred with respect to a SN explosion if we want the BH to be rather massive). At this stage the system is still quite large (hundreds to thousands of solar radii)(see.Fig.3.1). When also the secondary leaves the MS, growing in radius, the system can enter a CE phase. If two stars enter in common envelope (CE), their envelope(s) stop co-rotating with their cores. The two stellar cores (or the compact remnant and the core of the star, if the binary is already single degenerate) are embedded in the same non-co-rotating envelope and start spiralling in as an effect of gas drag exerted by the envelope. Part of the orbital energy lost by the cores as an effect of this drag is likely converted into heating of the envelope, making it more loosely bound. If this process leads to the ejection of the envelope, then the binary survives, but the post-CE binary is composed of two naked stellar cores (or a

compact remnant and a naked stellar core). Moreover the orbital separation of the two cores (or the orbital separation of the compact remnant and the core) is considerably smaller than the initial orbital separation of the binary, as an effect of the spiral-in.This circumstance is crucial for the fate of BH binary. in fact, if the binary which survives a CE phase evolves into a double BH binary, this double BH binary will have a very short semi-major axis, much shorter than the sum of the maximum radii of the progenitor stars, and may be able to merge by GW emission within a Hubble time. In contrast, if the envelope is not ejected, the two cores (or the compact remnant and the core) spiral in till they eventually merge. This premature merger of a binary during a CE phase prevents the binary from evolving into a double BH binary (see. Fig 3.1)

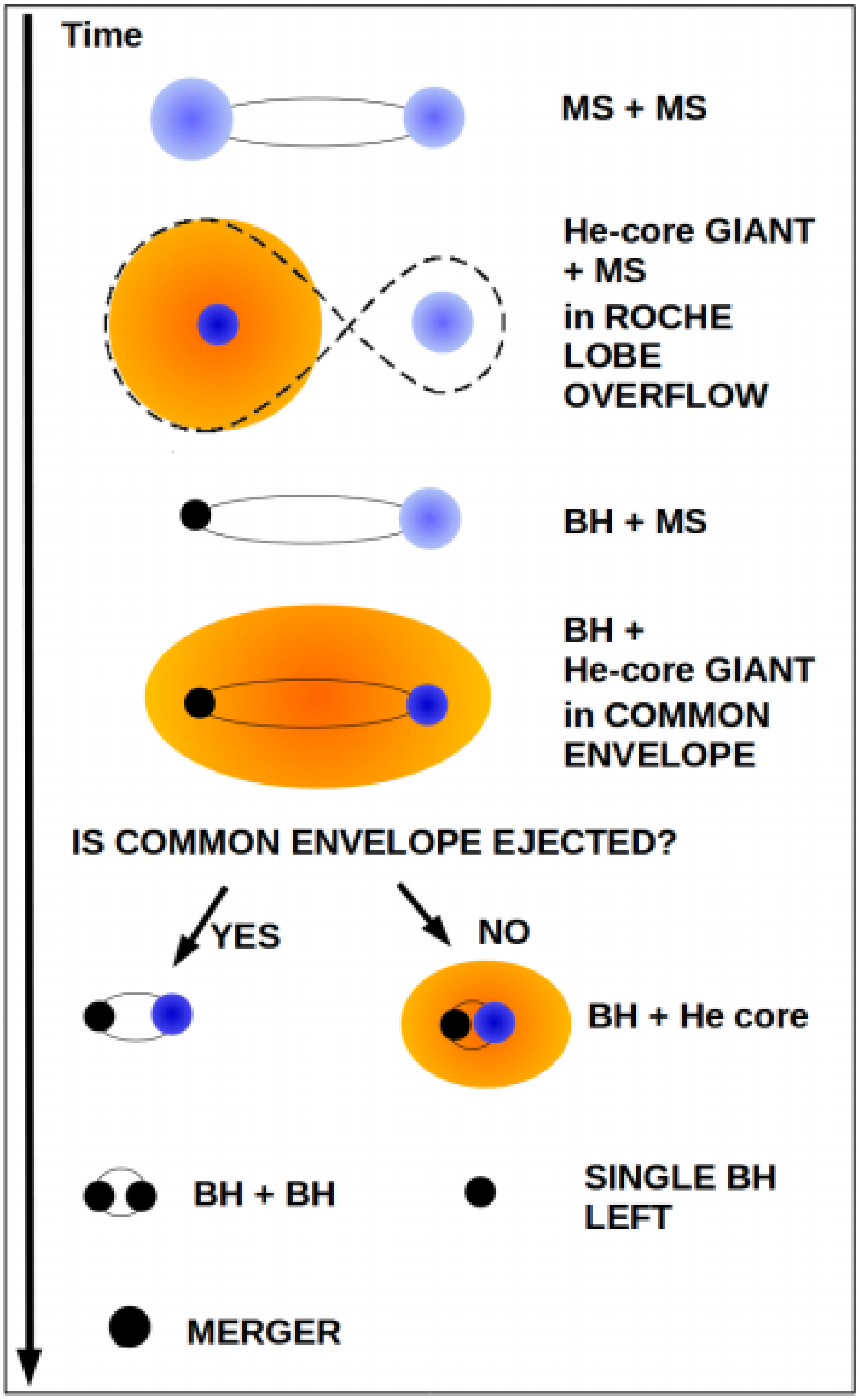
Time
MS + MS
He-core GIANT
+ MS
in ROCHE
LOBE
OVERFLOW
BH + MS
BH +
He-core GIANT
in COMMON
ENVELOPE
IS COMMON ENVELOPE EJECTED?
YES
NO
BH + He core
BH + BH
SINGLE BH
LEFT
MERGER

Figura 3.1: scheme of the evolution of a black hole binary through a common envelope phase. [From Mapelli, 2018(3)]

3.1 The $\alpha\lambda$ formalism

The$\alpha\lambda$ formalism is the most common formalism adopted to describe a common envelope. The basic idea is that the energy needed to unbind the envelope comes uniquely from the loss of orbital energy of the two cores during the spiral in. In the following, I will present the version of the $\alpha\lambda$ formalism described in Hurley et al. (2002)$^{(7)}$. The fraction The fraction of the orbital energy of the two cores which goes into unbinding the envelope can be expressed as:

$$\Delta E = \alpha(E_{b,f} - E_{b,fi}) = \alpha\frac{G m_{c1} m_{c2}}{2}(\frac{1}{a_f} - \frac{1}{a_i}).$$

where $E_{b,i}$ ($E_{b,f}$) is the orbital binding energy of the two cores before (after) the CE phase, a_i (a_f) is the semi-major axis before (after) the CE phase, m_{c1} and m_{c2} are the masses of the two cores, and α is a dimensionless parameter that measures which fraction of the removed orbital energy is transferred to the envelope. If the primary is already a compact object m_{c2} is the mass of the compact object. The binding energy of the envelope is:

$$E_{env} = \frac{G}{\lambda}[\frac{m_{env,1} m_1}{R_1} + \frac{m_{env,2} m_2}{R_2}]$$

where m_1 and m_2 are the masses of primary and the secondary member of the binary, $m_{env,1}$ and $m_{env,2}$ are the masses of the envelope of the primary and the secondary member of the binary and λ is the parameter which measures the concentration of the envelope (the smaller λ is, the more concentrated is the envelope) By imposing $\Delta E = E_{env}$ we can derive what is the final value of the final semi major axis a_f for which the envelope is ejected:

$$\frac{1}{a_f} = \frac{1}{\alpha\lambda}\frac{2}{m_{c1} m_{c2}}[\frac{m_{env,1} m_1}{R_1} + \frac{m_{env,2} m_2}{R_2}] + \frac{1}{a_i}$$

If a_f is lower than the sum of the radii of the two cores (or than the sum of the Roche lobe radii of the cores) then the binary will merge during the common envelope, otherwise the binary survives and this equation tells us the final orbital separation. This means that the larger (smaller) $\alpha\lambda$ is, the larger (smaller) the final orbital separation. So, the most critical quantities in the CE process are the masses of the two stars and also their initial separation: a BHB can merge within a Hubble time only if its initial orbital separation is tremendously small (few tens of solar radii, unless eccentricity is rather extreme); but a massive star ($>20 M\odot$) can reach a radius of several thousand solar radii during its evolution. Thus, if the initial orbital separation of the stellar binary is tens of solar radii, the binary merges before it can become a

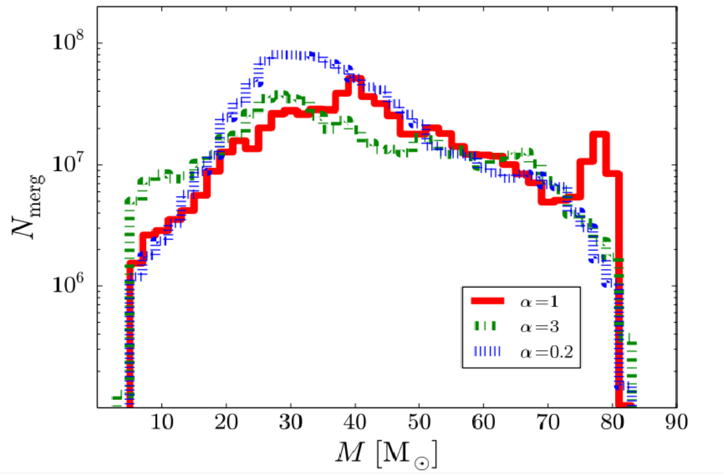

Figura 3.2: Distribution of total masses $M = m_1 + m_2$ of merging BH binaries in the LIGO-Virgo instrumental horizon. The only difference between the three histograms is the value of α in the CE formalism. Red solid line: α = 1; green dot-dashed line: α= 3; blue dotted line: α = 0.2. [From Mapelli 2018(4)]

BHB. On the other hand, if its initial orbital separation is too large, the two BHs will never merge. In this scenario, the two BHs can merge only if the initial orbital separation of the progenitor stellar binary is in the range which allows the binary enter CE and then to leave a short period BHB. This range of initial orbital separations dramatically depends on CE efficiency and on the details of stellar mass and radius evolution. Actually, we have known for a long time that this simple formalism is a poor description of the physics of CE, which is considerably more complicated. For example, there is a number of observed systems for which an $\alpha > 1$ is required,which is obviously unphysical. Moreover, λ cannot be the same for all stars. It is expected to vary widely not only from star to star, but also during different evolutionary stages of the same star. Figure 3.2 shows the distribution of total masses of merging BHs obtained with the same code (MOBSE), by changing solely the value of α (while λ is calculated self-consistently by the code). The difference between the three mass distributions is a clear example of how important is CE for the demography of BH binaries.

Thus, it would be extremely important to model the CE in detail, for example with numerical simulations. A lot of effort has been put on this in the last few years,but there are still many open questions. For example, we do not have self-consistent models on the onset of CE, when an unstable mass transfer prevents the envelope from co-rotating with the core. Usually, hydro-dynamical simulations of CE start when the core of the companion is already at the surface of the envelope. The only part of CE which has been successfully modelled is the initial spiral-in phase, when the two cores spiral in on a dynamical time scale (≈ 100 days)

3.2 Alternative evolution from CE

Massive fast rotating stars can have a chemically homogeneous evolution (CHE): they do not develop a chemical composition gradient because of the mixing induced by rotation. This is true if the star is metal poor (Merchant et al, 2016), because stellar winds are not very efficient in removing angular momentum.If a binary is very close, the spins of its members are even increased during stellar life by tidal synchronization. If metallicity is sufficiently low and rotation sufficiently fast, these binaries may evolve as 'over-contact' binaries: the over contact phase differs from classical CE phase because co-rotation can, in principle, be maintained as long as the material does not overflow the L2 point.This means that a spiral-in that is due to viscous drag can be avoided, resulting in a stable system evolving on a nuclear timescale. Such 'over contact' binaries maintain relatively small stellar radii during their evolution (few ten solar radii) and may evolve into a double BH binary with a very short orbital period. This scenario predicts the formation of merging BHs with relatively large masses ($>20 M_\odot$), nearly equal mass and with larger alligned spins.

Capitolo 4

Simulation of isolated binary systems

Using a population-synthesis code (MOBSE, from Giacobbo et al.2018$^{(8)}$), I've studied two systems of binaries (Z=0.002 Z$\odot$). Both evolves into a BHB (and merge within a Hubble time) but only one of them goes through a common envelope (CE) phase.
Population-synthesis codes evolve isolated binary systems by taking into account single star evolution (in the case of MOBSE this is done thanks to the polynomial fitting formulas developed by Hurley et al. 2000$^{(9)}$ plus a new formalism for stellar winds described in Giacobbo & Mapelli 2018$^{(10)}$), binary evolution processes (mass transfer, common envelope, tidal evolution and gravitational wave decay, as described in Hurley et al. 2002$^{(11)}$) and the outcomes of supernova explosions (in the form of semi-empirical prescriptions for natal kicks and compact object mass). The aim of this simulations is to highlight the main differences between the two evolution processes in physical parameters like the mass of the stars, their core mass, their separation and the eccentricity of the orbit.

4.1 Evolution through common envelope

Figure 4.1 shows the evolution with time of the masses of the two stars in the binary system which goes through a CE phase. We can see from this plot that for the first 5 Myr the primary loses mass due to stellar winds (in this case stellar winds are not so efficient because the star is not very massive $m_{ZAMS}\approx 43M\odot$).After $\approx$ 5 Myr the primary leaves the main sequence and approach the red giant branch. Here the star starts expanding and so its

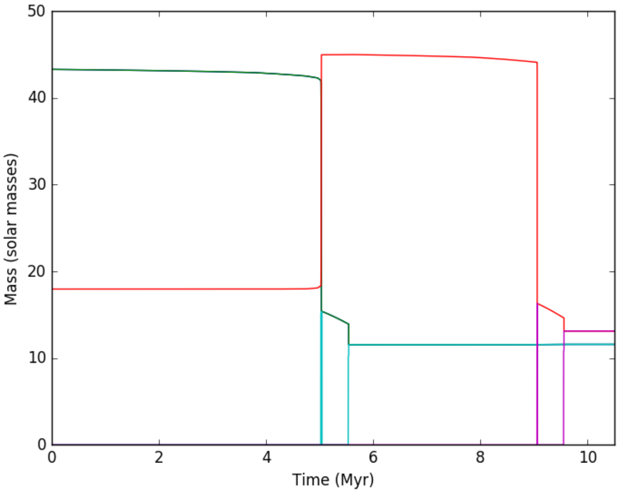

Figura 4.1: evolution with time of the masses of the two stars in the binary system which goes through a CE phase. The green line is the mass of the primary $m_{ZAMS} \approx 43M\odot$ (with the cyan line representing its core-mass). The red line is the mass of the secondary $m_{ZAMS} \approx 17M\odot$ (with the purple line representing its core-mass).The plot represents the lives of the stars from their birth to the time they both become BHs.

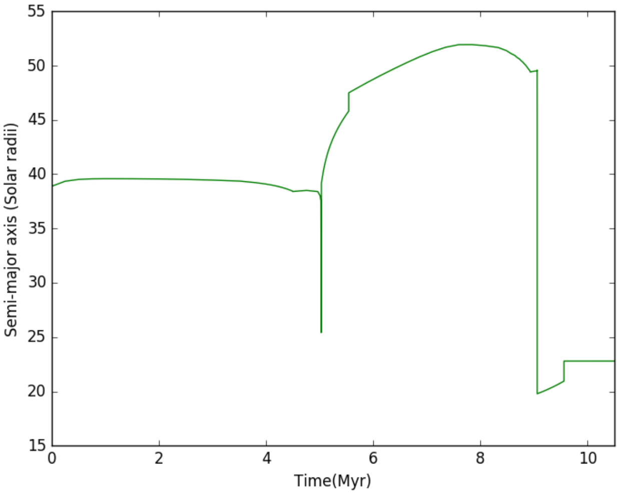

Figura 4.2: evolution of the orbital separation in the first 10Myr of life of the two stars. This system evolves through a CE phase

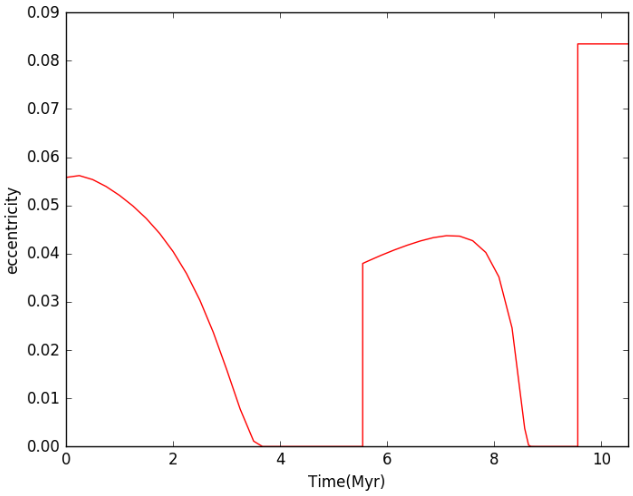

Figura 4.3: evolution with time of the eccentricity in the first 10.5 Myr of the binary (with CE)

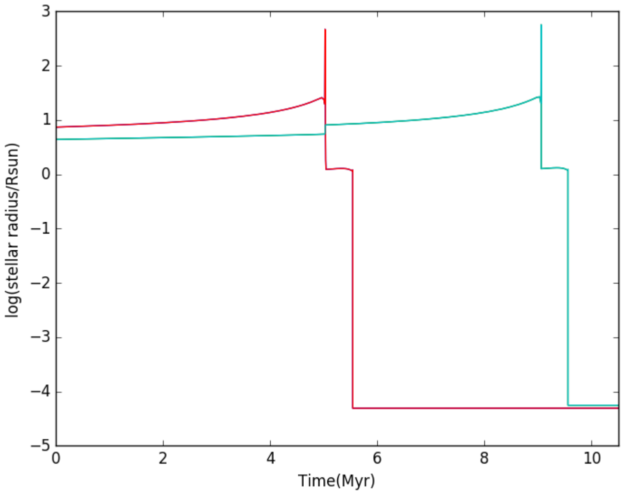

Figura 4.4: evolution with time of the radii of the two stars

radius starts growing until it will over fill the Roche globe. At this point $t \approx 5$ Myr) the mass transfer by Roche lobe overfilling from the primary to the secondary begin. At the end of this process the star has lost all of his envelope and the remnant is a naked Helium core: the star has become a Wolf-Rayet star and in the plot we can see this phase of the evolution because the mass of the core equals the total mass of the star (from $t \approx 5$ to $5.5 Myr$).Then, after a weak core-collapse supernova explosion the primary becomes a black hole with mass $m_{BH} \approx 12 M\odot$. For the secondary star ($m_{ZAMS} = 17 M\odot$) mass loss due to stellar winds is not efficient during his main-sequence lifetime because it's mass is too small. During the first Roche lobe overfilling its mass increases due to the mass transfer from the primary. At $t \approx 9 Myr$ the secondary over fills the Roche lobe and the system goes through a phase of common envelope. In this case the scenario is a black hole and a massive star surrounded by a unique envelope, because the primary has already became a compact object. During this process the mass of the secondary goes from $\approx 44 M\odot$ to $\approx 12 M\odot$. After this process the envelope is ejected and so also the secondary became a Wolf-Rayet star (in the plot $m_{core} = m_2$) and finally after a core collapse supernova explosion it become a black hole with mass $\approx 13 M\odot$.

Figure 4.2 represents the evolution of the orbital separation in the first 10 Myr of life of the system. The first dip of the plot is caused by the first Roche lobe overfill by the primary. In fact, a mass transfer process obviously changes the orbital properties of the system.At $t \approx 9 Myr$ the orbital separation strongly decreases during the common envelope phase where (for the reasons explained in Chapter 3) the separation between the two cores decreases due to the drag force exerted by the non co-rotating envelope.

Figure 4.3 show the trend of the eccentricity of the orbit in the binary systems from the birth of the stars to the time they become BHs. We see that the mass transfer processes by Roche lobe overfilling and also in the CE phase tends to circularize the orbit of the system. On the other hand, when one of the stars becomes a black hole, the mass loss due to the core collapse supernova explosion changes the orbital properties of the system and so, in these cases, the eccentricity increases.

From figure 4.4 we can see the evolution of the radii of the two stars. We can notice that as each star leaves the main sequence his radius starts inflating, and this leads to the various mass transfer processes. Then, when the star becomes a Wolf-Rayet, the core collapse supernova explosion occurs and the star becomes a BH, his radius drops (radius$<$0 means that the star has become a BH).

4.2 Evolution without common envelope

Figure 4.5 shows the evolution of the binary which does not go through a phase of CE. Here the evolution processes are the same as in the first case a part from the fact that the mass loss at $\approx 5.7 Myr$ is due to a strong Roche lobe overfilling by the secondary and not to a CE phase. Also, in this case the stars are more massive than in the first case ($m_1 \approx 102 M\odot$ and $m_2 \approx 47 M\odot$) so the mass losses due to stellar winds are more efficient.Also, during the first mass transfer episode the primary star overfills its Roche lobe by a much larger factor ($R_1/R_L \approx 280$) than it happened for the other binary system (where the primary overfills its Roche lobe by ≈ 30). Figure 4.6 shows the evolution of the orbital separation in the first 7 Myr. We can see that, like in the first case, the first dip is caused by the Roche lobe overfill by the primary. In this plot the changes (the separation increases) due to the core collapse supernova explosion of the primary are more evident (the separation goes from $\approx 64 R\odot$ to $\approx 73 R\odot$ when the primary become al black hole at t$\approx 3.8 Myr$). In this case, though, the strong decrease of the orbital separation at t$\approx 5.8 Myr$ is due to a mass transfer process by Roche lobe overfilling by the secondary. Like in the first case, we see from Fig. 4.7 that the mass transfer episodes by Roche lobe overfilling tend to circularize the orbit, but when one of the stars becomes a BH (with a core collapse supernova explosion) the eccentricity increases.

The evolution of the radii of the stars is similar to the first case (see Fig. 4.8).

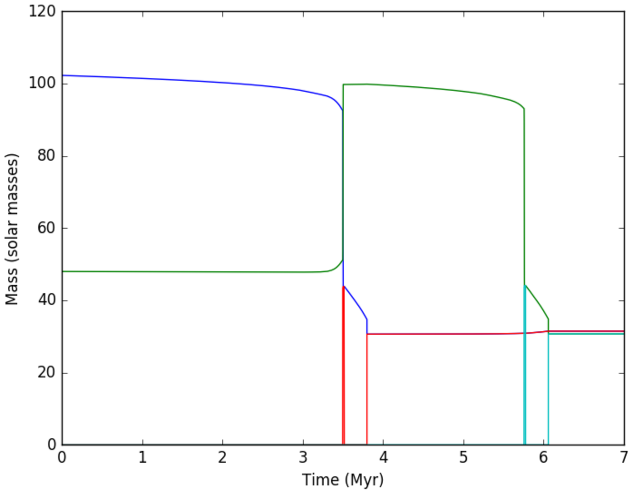

Figura 4.5: evolution with time of the masses of the two stars in the binary system which doesn't go through a CE phase. The blue line is the mass of the primary $m_{ZAMS} \approx 102M\odot$ (with the red line representing its core-mass). The green line is the mass of the secondary $m_{ZAMS} \approx 47M\odot$ (with the cyan line representing its core-mass).The plot represents the lives of the stars from their birth to the time they both become BHs.

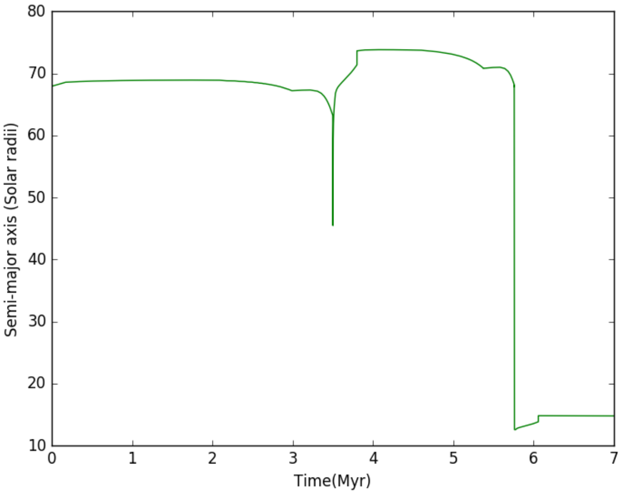

Figura 4.6: evolution of the orbital separation in the first 7Myr of life of the two stars. This system does not evolve through a CE phase

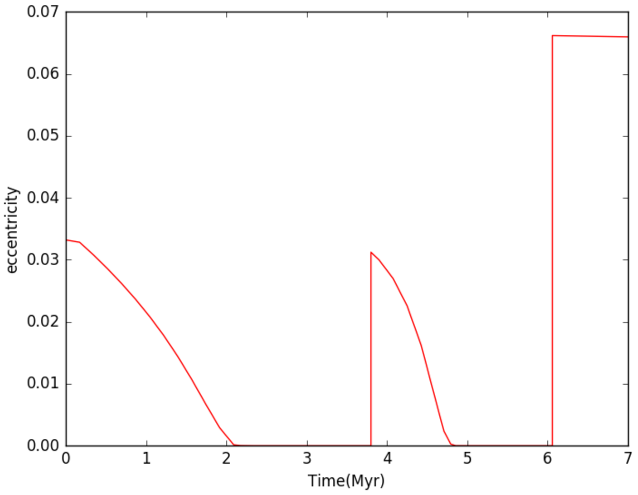

Figura 4.7: evolution with time of the eccentricity in the first 6.5 Myr of the binary (with no CE)

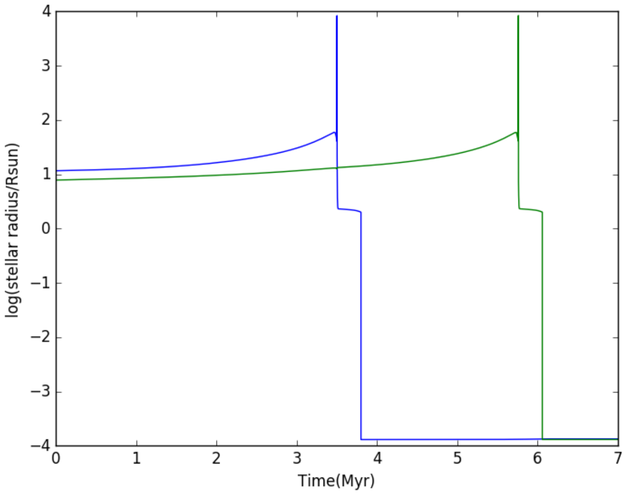

Figura 4.8: evolution with time of the radii of the two stars

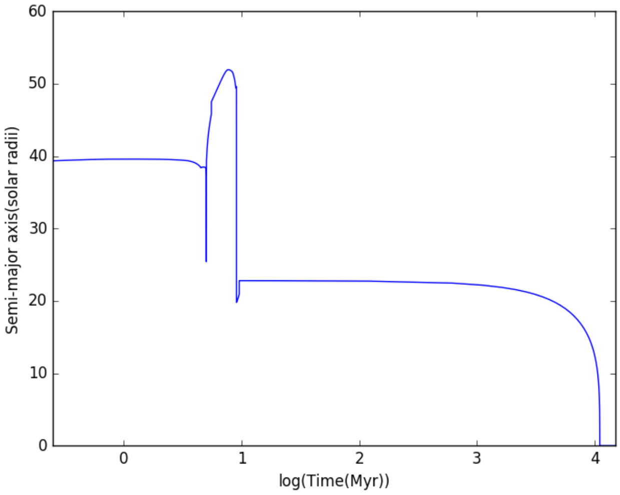

Figura 4.9: evolution of the orbital separation from the birth of the two stars to the black hole merger. This system evolves through a CE phase

Figure 4.9 and 4.10 show, instead, the general trends of the orbital separation of each system (4.7 with CE, 4.8 with no CE). We can highlight the fact that the system which doesn't evolve through a phase of common envelope will merge long before the system with the CE phase ($t_{m,noCE} \approx 133 Myr$, $t_{m,CE} \approx 11000 Myr$). This aspect is due to lots of factors, for example the difference of initial masses and orbital separation between the two systems.

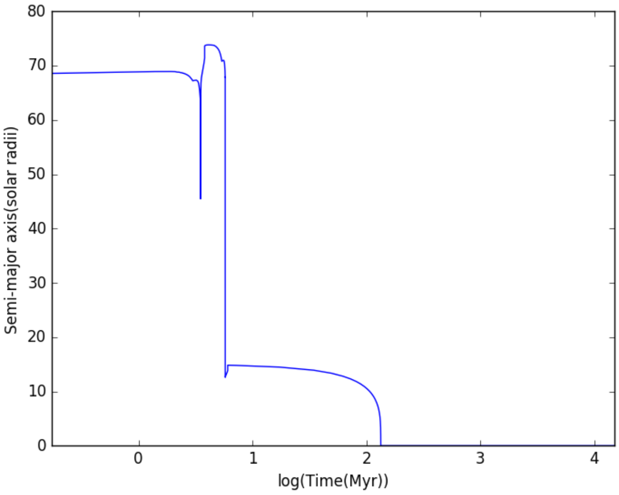

Figura 4.10: evolution of the orbital separation from the birth of the two stars to the black hole merge. This system doesn't evolve through a CE phase

Conclusions

In the first part of this Thesis, we have reviewed the importance of studying the evolution of massive binary stars to understand the formation of binary black holes. Starting from the processes that determine the final masses of the stars (and of the compact remnants)to the various mass transfer mechanisms,we have highlighted the main evolutionary processes in a close binary system focusing on common envelope. We have studied the most important aspects and the main open issues of this process. In the second part, we have analyzed two binary stars simulated by means of a population-synthesis code. Both binary stars become binary black holes and merge within a Hubble time. The first system we have considered evolves first through a Roche lobe overflow and then (after the primary has become a black hole) through a common envelope phase, which shrinks its orbital separation from $\approx 50R\odot$ to $\approx 20R\odot$ After common envelope, the binary black hole evolves just by gravitational-wave decay till it reaches coalescence in ≈11 Gyr. The masses of the two black holes in this system are quite low $\approx 10 - 15M\odot$). The second system we have considered evolves through two subsequent Roche lobe overflow episodes. The second one happens when the primary has already become a black hole and shrinks the semi-major axis from $\approx 70R\odot$ to $\approx 15R\odot$. After the second Roche lobe overflow episode, the secondary becomes a black hole and the system shrinks by gravitational-wave decay merging in $\approx 130Myr$. The masses of the two black holes in this system are significantly larger (≈ 30 M⊙). The larger masses of the two black holes and the smaller orbital separation after Roche lobe explain why the merger happens much faster.

Our preliminary investigation shows that, in order to evolve into a merging binary black hole without undergoing a common envelope phase, a massive binary system needs to go through a second phase of stable mass transfer. This second phase of mass transfer must induce a significant shrinking of the semi-major axis, comparable to the effect of a common envelope.

This result suggests that we must further investigate the details of Roche

lobe mass transfer and common envelope, by considering a larger sample of binaries. What is the fraction of systems that reach coalescence without undergoing common envelope? Do all of them go through two episodes of stable mass transfer? Is there any relationship between common envelope evolution and the final mass of the two black holes? Is there any dependence of this on the metallicity of the progenitor stars?
Finally, we know that the treatment of mass transfer in population-synthesis simulations suffers from several approximations. Hence, a further development of this Thesis would be to investigate a more accurate formalism for Roche lobe overflow and its impact on the demography of binary black holes.

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