PROCEEDINGS OF SCIENCE

Unravelling the progenitors of merging black hole binaries

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The recent detection of gravitational waves has proven the existence of massive stellar black hole binaries (BBHs), but the formation channels of BBHs are still an open question. Here, we investigate the demography of BBHs by using our new population-synthesis code MOBSE. MOBSE is an updated version of the widely used binary population-synthesis code BSE [6, 7] and includes the key ingredients to determine the fate of massive stars: up-to-date stellar wind prescriptions and supernova models. With MOBSE, we form BBHs with total mass up to ~ 120 $M_{\odot}$ at low metallicity, but only systems with total mass up to ~ 80 $M_{\odot}$ merge in less than a Hubble time. Our results show that only massive metal-poor stars ($Z \lesssim 0.002$) can be the progenitors of gravitational wave events like GW150914. Moreover, we predict that merging BBHs form much more efficiently from metal-poor than from metal-rich stars.

GRAvitational-waves Science&technology Symposium - GRASS2018
1-2 March 2018
Palazzo Moroni, Padova (Italy)

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1. Introduction

The recent direct detection of gravitational waves (GWs, [1, 2, 3, 4]) has revolutionized our knowledge about black holes (BHs). GW events confirm the existence of black hole binaries (BBHs) and prove that stellar mass BHs can be rather massive, with mass $\gtrsim 30\ M_{\odot}$ as in the case of GW150914, GW170104 and GW170814. Despite the formation and evolution of BBHs have been studied for a long time, the state-of-the-art theoretical models still suffer from many uncertainties. This is particularly true for the final stages of massive star evolution. Some of the major issues are the treatment of stellar winds and core-collapse supernovae (SNe). Here, we investigate the demography of BBHs by using our new up-to-date population-synthesis code MOBSE (which stands for "Massive Objects in Binary Stellar Evolution" [5]).

2. Description of MOBSE

MOBSE is an updated version of the widely used binary population-synthesis code BSE [6, 7]. In MOBSE, we introduced many upgrades with respect to BSE, with the main purpose of improving the treatment of massive stars and stellar remnants.

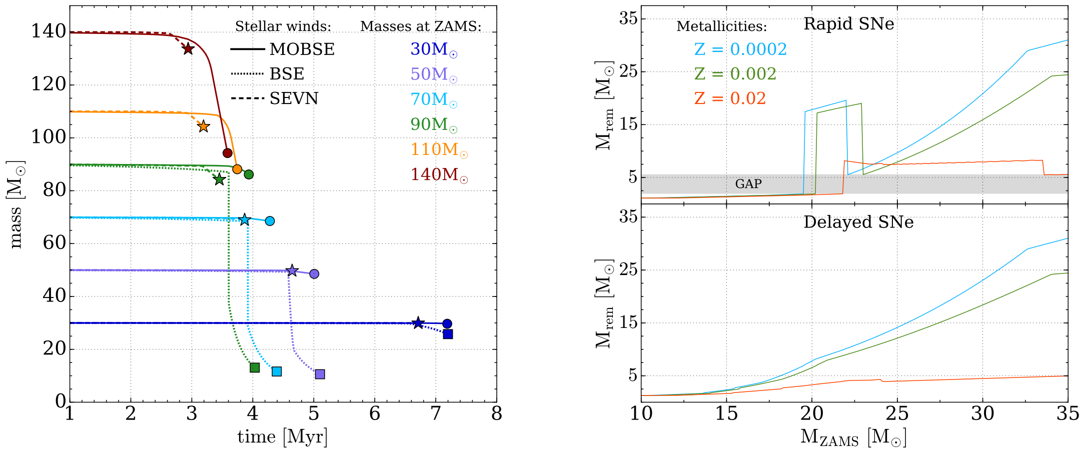

Figure 1: a) Stellar mass as a function of time for six zero-age main sequence (ZAMS) masses at $Z = 0.0002$ computed with MOBSE (solid lines), BSE (dotted) and SEVN (dashed). The markers identify the final mass of the stars: circles for MOBSE, squares for BSE and stars for SEVN. b) Mass of the compact remnant ($M_{\rm rem}$) as a function of the ZAMS mass of the progenitor star ($M_{\rm ZAMS}$) for the rapid (upper panel) and delayed SN model (bottom panel). Red lines: $Z = 0.02$; green lines: $Z = 0.002$; blue lines: $Z = 0.0002$. In the top panel, the mass gap between the heaviest neutron stars and the lightest BHs ($\sim 2\ M_{\odot}$ to $\sim 5\ M_{\odot}$) is highlighted by a shaded area. ZAMS masses larger than $35\ M_{\odot}$ are not shown because the outcomes of the rapid and delayed SN models are indistinguishable.

In particular, we model the mass loss of hot massive stars as $\dot{M} \propto Z^{\beta}$, where Z is the metallicity. The value of β depends on the Eddington factor (Γ_e): $\beta = 0.85$ if $\Gamma_e < 2/3$, $\beta = 2.45 - 2.4\Gamma_e$ if $2/3 \leq \Gamma_e < 1$ and $\beta = 0.05$ if $\Gamma_e \geq 1$ [8]. Hence, when a massive star approaches and/or exceeds the Eddington limit its mass loss becomes almost insensitive to the metallicity.

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We added in MOBSE two prescriptions for the SN explosion, called *rapid* and *delayed* model (both described in details in [9]). The main difference between these SN prescriptions is the time at which the explosion occurs: $t < 0.25$ s ($t \gtrsim 0.5$ s) for the rapid (delayed) model. Finally, MOBSE includes recipes for pulsational pair-instability SNe and for pair-instability SNe, as described in [10]. The reader can find more details about MOBSE in [11, 5].

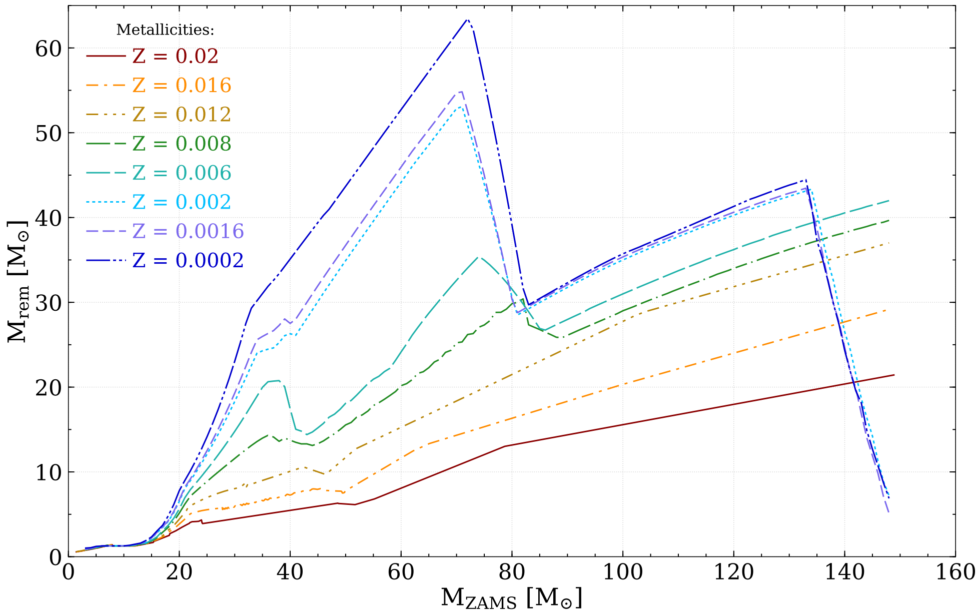

Figure 2: Mass spectrum of the compact remnants (M_{rem}) as a function of the zero-age main sequence (ZAMS) mass of progenitor stars, for different metallicity and adopting the delayed SN model.

3. Results

In the left-hand panel of Fig. 1 we compare the evolution of stellar mass at $Z = 0.0002$ derived from MOBSE with the evolution obtained with other two population-synthesis codes, namely BSE and SEVN [12, 10]. For large zero-age main sequence (ZAMS) masses, the behavior of BSE is completely different with respect to both MOBSE and SEVN. This difference is due to stellar wind prescriptions. The main difference between MOBSE and SEVN is the duration of stellar life. It is remarkable that MOBSE and SEVN behave so similarly, considering that MOBSE computes single stellar evolution by using fitting formulas (described in [6]), while SEVN uses up-to-date look-up tables based on PARSEC [8]. In the right-hand panels of Fig. 1, we compare the rapid and delayed SN models. The main difference is that the rapid model predicts a remnant mass gap between ~ 2 M$_\odot$ and ~ 5 M$_\odot$.

Fig. 2 shows the mass spectrum of compact remnants as a function of the ZAMS mass for 8 metallicities (ranging from $Z = 0.0002$ to $Z = 0.02$), adopting the delayed SN model. It is apparent that there is a strong correlation between the maximum mass of the remnants and the metallicity. In particular, the lower the metallicity is, the higher the mass of the most massive remnant.

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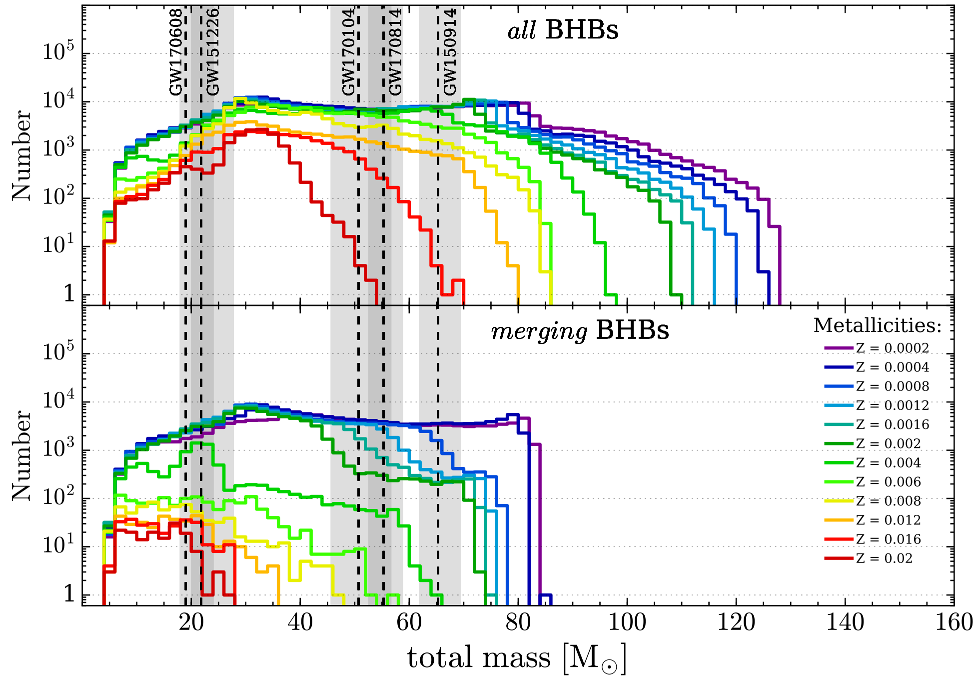

Figure 3: Total mass distribution for all BBHs (upper panel) and for the merging BBHs (lower panel) simulating 10^7 binaries for each metallicity. Vertical dashed lines: total mass of GW150914, GW151226, GW170104, GW170608 and GW170814, with the corresponding 90 % credible intervals (shadowed regions) [1, 2, 3, 4].

Fig. 3 shows the distribution of total mass ($m_1 + m_2$, where $m1$ and $m2$ are the masses of the primary and of the secondary BH, respectively) of BBHs formed in our simulations, considering different metallicities (10^7 binaries for each metallicity) and adopting the delayed SN model. In the top panel, we show the total mass distribution of all BBHs while in the bottom panel we show only the distribution for the sub-sample of systems merging within a Hubble time. As expected, the maximum mass of BBHs is higher at lower metallicity. From this Figure, it is also apparent that for a given metallicity the maximum mass of non-merging systems (~ 120 M$_\odot$ at $Z = 0.0002$) is significantly larger than the maximum mass of merging systems (~ 80 M$_\odot$ at $Z = 0.0002$). Moreover, the number of merging systems strongly depends on the metallicity, namely decreasing Z the number of merging BBHs rises. Our results are consistent with the total mass of the five GWs detections of merging BBHs, but we find that only metal-poor stars can be the progenitors of the most massive merging systems like GW170104 ($Z \lesssim 0.006$), GW170814 ($Z \lesssim 0.004$) and GW150914 ($Z \lesssim 0.002$).

4. Summary

We present our new population-synthesis code MOBSE [11, 5]. In MOBSE we have implemented two prescriptions for SNe [9] and the most recent models of stellar winds [8]. In particular, we included in MOBSE also the effect of the Eddington factor on the mass loss. We used MOBSE

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for studying the formation and evolution of BBHs. We find that the lower the metallicity is, the higher the maximum mass of BBHs. We form BBHs with total mass up to ~ 120 M$_\odot$ at low metallicity, but only systems with total mass up to ~ 80 M$_\odot$ merge in less than a Hubble time.

The masses of our merging BBHs match those of the five reported BBH mergers. Only metal-poor progenitors can produce systems so massive as GW170104, GW170814 and GW150914. Finally, we find that merging BBHs form much more efficiently from metal-poor than from metal-rich progenitors.

Acknowledgments

NG acknowledges financial support from Fondazione Ing. Aldo Gini. MM acknowledges financial support from the MERAC Foundation, from INAF through PRIN-SKA 'Opening a new era in compact object science with MeerKat', and from FWF through FWF stand-alone grant P31154-N27.

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