Massive stars as progenitors of merging black hole binaries

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Introduction

Open question:
→ What are the formation mechanisms of binary black holes?

Purpose:
→ to study the demography of compact object binaries in different environments.

Issue:
→ most of current population-synthesis codes do not use recent stellar evolution models.
MOBSE (Massive Objects in Binary Stellar Evolution)

**BSE:** includes obsolete stellar-evolution models:
- Tout+ 1997 for the stellar winds;
- Hurley+ 2000 for the supernova explosions (SNe).

**MOBSE:** major updates:
- recent stellar winds Vink+ 2001 and Gränefer+ 2011;

Updated version of the most popular and used population synthesis code (Hurley+ 2002).
Upgrades: stellar winds

The **main differences** with respect to the **old recipes** for the stellar winds are:

Dependence on metallicity $Z$ during **Wolf-Rayet** phase and **Luminous Blue Variable** stars:

$$
\dot{M} \propto Z^\alpha \, M_\odot \, \text{yr}^{-1}
$$

\[
\begin{cases}
\alpha = 0.85 & \Gamma_e < \frac{2}{3} \\
\alpha = 2.45 - 2.4 \Gamma_e & \frac{2}{3} \leq \Gamma_e \leq 1
\end{cases}
\]

Effect of the electron - scattering **Eddington factor** on mass loss: (Chen+ 2015)
Upgrades: SNe models

Implementation of two new SNe models described in Fryer+ (2012).

**Rapid SNe:**
explosion occurs at \( t \lesssim 250 \) ms after the bounce.

**Delayed SNe:**
explosion occurs after \( t \gtrsim 0.5 \) s from the bounce.
Mass spectrum
BHBs Demography with MOBSE

Grid of initial conditions:

\[ Z \rightarrow 12 \text{ metallicity} \in [0.02 - 0.0002]; \]

systems \( \rightarrow 10^7 \) for each metallicity;

Distributions proposed by Sana+ 2012:

\[ M_1 \rightarrow \text{IMF of Kroupa+ 2001 in } M_1 \in [5 - 150]M\odot; \]

\[ M_2 \rightarrow \text{uniform distribution of } M_2 \in [0.1 - 1.0]M_1; \]

\[ e \rightarrow \text{uniform distribution of } e^{-0.42} \in [0.0 - 1.0]; \]

\[ P \rightarrow \text{uniform distribution of } \log_{10}(P/\text{day})^{-0.55} \in [0.15 - 5.5]. \]

Mass BHBs

NG+ 2018

![Mass BHBs graph](Image)

- **Number** vs. **total mass [M_☉]**
- **all BHBs**
- **merging BHBs**
- **Metallicities:**
  - $Z = 0.0002$
  - $Z = 0.0004$
  - $Z = 0.0008$
  - $Z = 0.0012$
  - $Z = 0.0016$
  - $Z = 0.002$
  - $Z = 0.004$
  - $Z = 0.006$
  - $Z = 0.008$
  - $Z = 0.012$
  - $Z = 0.016$
  - $Z = 0.02$
Common-Envelope

CE critical phase for the formation of compact object binaries.

Energy conservation formalism: $\alpha \lambda$

$$\alpha \left( \frac{Gm_1 m_2}{2a_i} - \frac{Gm_{1,\text{core}} m_2}{2a_f} \right) = -\frac{Gm_1 m_{1,\text{env}}}{\lambda R_1}$$

$\alpha \rightarrow$ efficiency transfer of orbital energy to the common envelope.

$\lambda \rightarrow$ describes the binding energy of the common envelope.
Merger per unit mass

\[ R = \frac{N_{\text{merger}}}{M_{\text{tot, sim}}} \]

\[ R_{\text{cor}} = f_{\text{bin}} f_{\text{IMF}} R \]

\[ f_{\text{bin}} = 0.5 \quad \rightarrow \quad \text{we assume 50 per cent of binary} \]
\[ f_{\text{IMF}} = 0.285 \quad \rightarrow \quad \text{we simulate only } M_1 \geq 5 \, M_\odot \]
Merger per unit mass

\[ R_{\text{cor}} \left[ M_\odot^{-1} \right] \]

- **Delayed, \( \alpha = 1.0 \)**
- **Delayed, \( \alpha = 3.0 \)**
- **Delayed, \( \alpha = 0.2 \)**
- **Rapid, \( \alpha = 1.0 \)**
Conclusions

1. → the heaviest BHs ($\sim 60 \, M_\odot$) formed at $Z \lesssim 0.002$;

2. → the most massive BHBs ($\gtrsim 85 \, M_\odot$) do not merge;

3. → the masses of our merging BHBs match those of the five reported GW events;

4. → merging BHBs form much more efficiently from metal-poor ($R_{\text{cor}} \sim 10^{-4} \, M_\odot^{-1}$) than from metal-rich ($R_{\text{cor}} \sim 10^{-7} \, M_\odot^{-1}$) binaries.