Live fast and die young

Evolution and fate of massive stars

Renzo, M.

Publication date
2019

Document Version
Other version

License
Other

Link to publication

Citation for published version (APA):
Renzo, M. (2019). *Live fast and die young: Evolution and fate of massive stars*.

D
Mind the gap: The location of the pair instability supernovae black hole mass gap

D.1 Analytic fits for population synthesis

Population synthesis studies of the impact of PPI on the gravitational wave mergers distributions have relied on numerical fits to the results of Woosley (2017) expressed as a function of the helium core mass (e.g., Belczynski et al. 2016b; Spera & Mapelli 2017; Stevenson et al. 2019). However, at high metallicites we find the stars are stripped of all helium, leaving a bare CO core. As the CO core mass at the time of core-collapse is a quantity that is available in population synthesis calculations (although possibly defined differently compared to here, Hurley et al. 2000), we recommend to use $M_{\rm CO}$ as the independent variable to determine the final BH mass of stars. Though this only applies to stars that have lost their hydrogen envelopes either in binary interactions or due to wind mass loss.

For any given choice of physics and numerics, the second most important parameter, after $M_{\rm CO}$, determining the final BH mass is the initial metallicity of the star Z. We provide an approximate fit to the BH masses in figure 6.2 in terms of these two parameters:

$$M_{\rm BH} = \begin{cases} M_{\rm CO} & M_{\rm CO} < 38\ , \\ a_1 M_{\rm CO}^2 + a_2 M_{\rm CO} + a_3 \log_{10}(Z) + a_4 & 38 \leq M_{\rm CO} \leq 60 \\ 0.0 & 60 < M_{\rm CO}\ , \end{cases} \tag{D.1}$$

where $a_1 = -0.1027$, $a_2 = 9.1355$, $a_3 = -2.1588$, and $a_4 = -166.1884$, where all masses are in $M_\odot$ and is accurate to $\approx 20\%$.

We note that for $M_{\rm CO} < 38\,M_\odot$ weak pulses that do not result in significant mass ejection are still possible, and might have an effect on the orbital properties of a binary system (e.g., Marchant et al. 2018). Moreover, the fit of D.1 does not contain information on the mass lost per each individual pulse, and on the timing of the pulses, which might both influence the evolution in a binary.

Another important result of this study is the small sensitivity of the maximum BH mass below the pair instability gap to metallicity, with only a $\approx 15\%$ variation over a range in Z spanning 2.5 orders of magnitude. Therefore, the maximum BH mass might be used as a standard siren for cosmological applications once sufficiently large samples of BHs are detected.

We also provide an approximate fit to the maximum BH mass below the pair instability gap as a function of the metallicity which expresses this weak dependence:

$$M_{\rm BH,max} = b_1 + b_2 \log_{10}(Z) + b_3 \left[\log_{10}(Z)\right]^2 \quad , \tag{D.2}$$

where $b_1 = 25.13$, $b_2 = -9$, and $b_3 = -0.96$, where the resulting $M_{\rm BH,max}$ is in solar units and is accurate to $\approx 3\%$. This can be applied also to metallicities $Z < 10^{-5}$, lower than considered here, since we do not expect significant (line driven) wind mass loss in this regime. However it is unlikely to be valid for stars with $Z > 4 \times 10^{-3}$, due to their stronger winds that prevents the formation of sufficiently massive CO cores to experience PPI-driven mass loss.

D.2 Mass loss from progenitors

Table D.1 shows the amount of mass loss and final fate for our fiducial set of stellar parameters. A full version of the table for all models, is available online, for the other parameters considered here. Table D.1 shows: the initial (helium) mass; the helium and carbon/oxygen core masses, measured before the pulsations begin; the final BH mass; the mass lost in pulses; mass loss in winds; mass lost at the final supernovae; and the final fate of the star. The mass lost at supernovae is a combination of the mass loss due to material having a binding energy $< 10^{48}$erg s^{-1} and material that is in the process of being ejected (i.e., it is moving faster than the local escape velocity) but has not been removed from the model at the time of core collapse.

Table D.1: Fate of the mass of the progenitors, for our fiducial model with $Z = 10^{-3}$. A full table for all models, is available online

$M_{\rm init}$	$M_{\rm He}$	$M_{\rm CO}$	$M_{\rm BH}$	$\Delta M_{\rm pulse}$	$\Delta M_{\rm wind}$	$\Delta M_{\rm SN}$	Fate
30	26.12	22.55	26.05	0.00	3.88	0.08	CC
35	29.94	26.09	29.85	0.00	5.06	0.10	CC
40	33.66	29.57	33.60	0.00	6.34	0.06	CC
42	35.12	30.98	34.97	0.00	6.88	0.15	CC
44	36.57	32.32	36.43	0.00	7.43	0.14	CC
46	38.00	33.64	37.78	0.00	8.00	0.22	CC
48	39.42	34.95	38.38	0.00	8.58	1.04	CC
50	40.83	36.30	40.76	0.00	9.17	0.08	CC
52	42.23	37.55	41.97	0.00	9.77	0.26	CC
54	43.62	38.86	42.10	0.00	10.38	1.52	CC
56	44.99	40.16	43.60	0.00	11.01	1.39	CC
58	46.36	41.45	42.61	3.55	11.64	0.20	PPISN
60	47.71	42.73	43.08	4.33	12.29	0.30	PPISN
62	49.06	44.00	43.39	4.66	12.94	1.01	PPISN
64	50.39	45.40	42.62	6.63	13.61	1.14	PPISN
66	51.73	46.88	43.40	7.83	14.27	0.50	PPISN
68	53.04	48.19	42.00	10.27	14.96	0.78	PPISN
70	54.36	49.63	40.54	12.87	15.64	0.94	PPISN
72	55.70	51.00	39.49	15.24	16.30	0.97	PPISN
74	56.96	52.37	36.14	19.22	17.04	1.59	PPISN
76	58.25	53.82	34.21	23.26	17.75	0.78	PPISN
78	59.55	55.13	30.05	26.74	18.45	2.76	PPISN
80	60.83	56.51	14.85	45.88	19.17	0.11	PPISN
85	64.02	59.98	0.00	64.02	20.98	0.00	PISN
90	67.09	63.24	0.00	67.09	22.91	0.00	PISN
95	70.12	66.51	0.00	70.12	24.88	0.00	PISN
100	73.10	69.66	0.00	73.10	26.90	0.00	PISN
105	76.05	72.80	0.00	76.05	28.95	0.00	PISN
110	78.95	75.88	0.00	78.95	31.05	0.00	PISN