Explosions in massive binaries:

“widowed” stars and consequences for GW astronomy

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Why are massive stars important?

- Nucleosynthesis & Chemical Evolution
- Ionizing Radiation
- Star Formation
- Supernovae
- GW Astronomy
Why are massive stars important?

Nucleosynthesis & Chemical Evolution

Ionizing Radiation

Star Formation

Supernovae

GW Astronomy

∼70% of O type stars will interact with a companion

(e.g., Mason et al. '09, Sana & Evans '11, Sana et al. '12, Kiminki & Kobulnicky '12, Kobulnicky et al. '14, Almeida et al. '17)
BH or NS?
- Single stars winds impact on the core structure

Keep the stars together
- The most common evolution for massive binaries
- Constraints on BH kicks using runaway “widow”

The most massive (stellar) BHs
- (Pulsational) pair instability
- The BH mass distribution
  - Induced eccentricity

Conclusions
Outline

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Radiatively Driven Winds in One Slide

\[ \Delta p = \frac{h}{c} (\nu_i \cos(\theta_i) - \nu_f \cos(\theta_f)) \]

Problems: High Non-Linearity and Clumpiness
Clumpiness

Inhomogeneities:

\[ f_{\text{cl}} \overset{\text{def}}{=} \frac{\langle \rho^2 \rangle}{\langle \rho \rangle^2} \neq 1 \Rightarrow \dot{M} \neq 4\pi r^2 \rho v(r) \]
Risk:
Possible overestimation of the wind mass loss rate

Inhomogeneities:

\[ f_{cl} \overset{\text{def}}{=} \frac{\langle \rho^2 \rangle}{\langle \rho \rangle^2} \neq 1 \Rightarrow \dot{M} = \eta 4\pi r^2 \rho v(r) \]
Grid of $Z_{\odot}$ non-rotating models:

$$M_{\text{ZAMS}} = 15, 20, 25, 30, 35 \, M_{\odot}$$

$$\eta = 1, \frac{1}{3}, \frac{1}{10}$$

Combinations of wind mass loss rates for “hot” ($T_{\text{eff}} \geq 15 \,[\text{kK}]$), “cool” ($T_{\text{eff}} < 15 \,[\text{kK}]$) and WR:

Impact on the final mass

Legend:
- $\eta = 0.1$
- $\times \eta = 0.33$
- $+ \eta = 1.0$

$\eta \rightarrow$ largest uncertainty

$M / M_{ZAMS}$
$M_{ZAMS} [M_\odot]$
Impact on the final mass

\[ \frac{M}{M_{\text{ZAMS}}} \]

Legend:
- \( \bullet \quad \eta = 0.1 \)
- \( \times \quad \eta = 0.33 \)
- \( + \quad \eta = 1.0 \)

\( \eta \rightarrow \) largest uncertainty
Pre-explosion appearance

\[ \log_{10}(T_{\text{eff}}/[K]) \]

\[ \log_{10}(L/L_{\odot}) \]

BSG & WR

YSG

RSG

\eta = 1.0

\eta = 0.33

\eta = 0.1

Renzo et al. '17
Pre-explosion appearance

Same appearance with $\Delta M$ up to 50%

$\Rightarrow$ The internal structure re-adjusts to the wind mass loss
\[ \xi_M(t) \overset{\text{def}}{=} \frac{M/M_\odot}{R(M)/1000 \text{ km}} \]

Single parameter to describe the core structure

e.g., O’Connor & Ott ’11,
Ugliano et al. ’12,
Sukhbold & Woosley ’14,
but see (for 3D explosions):
Ott et al. ’18,
Kuroda et al. ’18

\[ M = 2.5 M_\odot \]

not to scale!
Core structure at O depletion

\[ M_{ZAMS} = 25 \, M_\odot \] MESA models

Critical point:
Ne core/C shell burning

\[ \eta = 1.0 \]
\[ \eta = 0.33 \]
\[ \eta = 0.1 \]
V-dJ
K-vL
V-vL
V-NJ
K-NJ
K-dJ

Log time to O depletion

\[ \log_{10}( (t_{O \, \text{depl}} - t) / [\text{yr}] ) \]
Post O burning evolution

Si shell burning $\rightarrow$

$\log_{10} \left( \frac{(t_{\text{pre-SN}} - t)}{[\text{yr}]} \right)$

- $15M_\odot$, $\eta = 1.0$
- $25M_\odot$, $\eta = 0.33$
- $30M_\odot$, $\eta = 0.33$

Renz et al. '17
Post O burning evolution

Si shell burning \( \rightarrow \)

\[ \log_{10} \left( \frac{(t_{\text{pre-SN}} - t)}{\text{[yr]}} \right) \]

\( \sim 30\% \) Uncertainty in \( \xi_{\text{pre-SN}}^{2.5} \) for given \( \eta \)

Uncertainties in the wind impact the pre-SN core

\[ 15M_\odot, \eta = 1.0 \]
\[ 25M_\odot, \eta = 0.33 \]
\[ 30M_\odot, \eta = 0.33 \]
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Methods: Population Synthesis

Fast ⇒ Allows statistical tests of the inputs & assumptions

SN kicks

Stellar Winds

Initial Distributions

Synthetic Population

RLOF & Common Envelope

Mass Transfer

Tidal Interactions

Izzard et al. '04, '06, '09; de Mink et al. '13
Spin up, pollution, and rejuvenation

The binary disruption shoots out the accretor

Spin up: Packet ’81, Cantiello et al. ’07, de Mink et al. ’13
Pollution: Blaauw ’93
Rejuvenation: Hellings ’83, Schneider et al. ’15
What exactly disrupts the binary?

$86^{+11}_{-9}\%$ of massive binaries are disrupted

- Unbinding Matter (e.g., Blaauw '61)
- Ejecta Impact (e.g., Wheeler et al. '75, Tauris & Takens '98, Liu et al. '15)
- SN Natal Kick (e.g., Shklovskii '70, Janka '16)

Renzo et al. arXiv:1804.09164, Eldridge et al. 11, De Donder et al. 97
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$$v_{\text{dis}} \sim v_{\text{pre-SN}}^{2, \text{orb}} = \frac{M_1}{M_1 + M_2} \sqrt{\frac{G(M_1 + M_2)}{a}}$$

Most binaries produce a slow “walkaway” star.
SN natal kick

Observationally: $v_{\text{pulsar}} \gg v_{\text{OB-stars}}$

Physically: $\nu$ emission and/or ejecta anisotropies

Credits: Ott, C. D., Drasco, S.
SN natal kick

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Massive runaways mass function ($v \geq 30\,\text{km}\,\text{s}^{-1}$, $M \geq 7.5\,M_\odot$)

Renzo et al., submitted, arXiv:1804.09164
A way to constrain BH kicks with *Gaia*

Massive runaways mass function ($\nu \geq 30\,\text{km s}^{-1}$, $M \geq 7.5\,M_\odot$)

BH momentum kick
($\sigma_{\text{kick}} = 265\,\text{km s}^{-1}$, fiducial)

Renzo et al., submitted, arXiv:1804.09164
A way to constrain BH kicks with Gaia

Massive runaways mass function \((v \geq 30 \text{ km s}^{-1}, M \geq 7.5 M_\odot)\)

- BH: \(\sigma_{\text{kick}} = 100 \text{ km s}^{-1}\)
- NS: \(\sigma_{\text{kick}} = 265 \text{ km s}^{-1}\)
  (no fallback for BH)

BH momentum kick
\((\sigma_{\text{kick}} = 265 \text{ km s}^{-1}, \text{fiducial})\)

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Massive runaways mass function ($v \geq 30\,\text{km}\,\text{s}^{-1}$, $M \geq 7.5\,M_\odot$)

- BH kick = NS kick ($\sigma_{\text{kick}} = 265\,\text{km}\,\text{s}^{-1}$)
  - (no fallback)

- BH: $\sigma_{\text{kick}} = 100\,\text{km}\,\text{s}^{-1}$
- NS: $\sigma_{\text{kick}} = 265\,\text{km}\,\text{s}^{-1}$
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BH momentum kick ($\sigma_{\text{kick}} = 265\,\text{km}\,\text{s}^{-1}$, fiducial)

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Radiation dominated:

\[ P_{\text{tot}} \simeq P_{\text{rad}} \]

\[ M_{\text{He}} \gtrsim 32 \, M_\odot \]

Woosley 2017,
Marchant, Renzo et al. arXiv:1810.13412,
Renzo, Farmer et al., to be submitted
\[ \Gamma_1 \overset{\text{def}}{=} \left( \frac{\partial \ln P}{\partial \ln \rho} \right)_s \]

1. Pair production
\[ \gamma \gamma \rightarrow e^+ e^- \]

\[ M_{\text{He}} = 46 \, M_\odot, \, Z = 0.001 \]

\[ \langle E_\gamma \rangle < E_{\text{Fermi}}^\pm \]

\[ \langle E_\gamma \rangle < 2m_e c^2 \]

\[ \Gamma_1 < 4/3 \]

\[ \rho \quad \text{[g cm}^{-3}\text{]} \]

He core computed with **MESA**
2. Softening of EOS triggers collapse
\[ \Gamma_1 < \frac{4}{3} \]

1. Pair production
\[ \gamma \gamma \rightarrow e^+ e^- \]

Thermal timescale
\[ \tau \propto \frac{GM_{\text{He}}^2}{RL_v}, \quad L_v \gg L \]

(Fraley 68)
2. Softening of EOS triggers collapse
\[ \Gamma_1 < \frac{4}{3} \]

3. Explosive (oxygen) ignition

1. Pair production
\[ \gamma \gamma \rightarrow e^+ e^- \]
2. Softening of EOS triggers collapse $\Gamma_1 < \frac{4}{3}$

3. Explosive (oxygen) ignition

4a. Pulse with mass ejection

4b. PISN: complete disruption

1. Pair production $\gamma\gamma \rightarrow e^+e^-$
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\[ \gamma \gamma \rightarrow e^+ e^- \]
2. Softening of EOS triggers collapse
\[ \Gamma_1 < \frac{4}{3} \]
3. Explosive (oxygen) ignition
4. Entropy loss and fuel depletion stabilize the core
5. \( \nu \)-cooling and contraction
6. BH
7. PISN: complete disruption
Example: $40 \, M_\odot$ He core

\begin{align*}
M_{\text{tot}} & \\
T_c & \\
\log_{10}\left\{\left(\frac{t_{cc} - t}{\text{[yr]}}\right)\right\} & 
\end{align*}

Log Time to core-collapse

Renzo, Farmer et al., to be submitted
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The origin of very massive BHs

Renzo, Farmer et al., (in prep.)
The origin of very massive BHs

$M_{\text{CO}} \left[ M_\odot \right]$ vs $M_{\text{He}} \left[ M_\odot \right]$ plot showing the relationship between the CO core mass and the He core mass. The points marked with 'CC' indicate certain events or conditions.

Renzo, Farmer et al., (in prep.)
The origin of very massive BHs

Renzo, Farmer et al., (in prep.)
The origin of very massive BHs

Renzo, Farmer et al., (in prep.)
Metallicity variations?

Other robustness tests:
- Spatial & temporal resolution
- Wind mass loss rate
- $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ rate

Farmer, Renzo, et al. (in prep.)
Takahashi 18
Woosley 17, 19

$\max\{\text{BH mass}\}$ robust as function of $M_{\text{CO}}$
(rate will vary with $Z$)
Metallicity variations?

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- Spatial & temporal resolution
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$\max\{\text{BH mass}\}$ robust as function of $M_{\text{CO}}$
(rate will vary with $Z$)
Chirp Mass Distribution

\[
dN \frac{dM}{dM_{\text{He}}} \propto M_{\text{He}}^{-2.35}
\]

\[
q \overset{\text{def}}{=} \frac{M_2}{M_1} \geq 0.5
\]

(motivated by LVC 2016)
Chirp Mass Distribution

\[ \frac{dN}{dM_{\text{He}}} \propto M_{\text{He}}^{-2.35} \]

\[ q \overset{\text{def}}{=} \frac{M_2}{M_1} \geq 0.5 \]

(motivated by LVC 2016)

Chirp Mass Distribution

LIGO/Virgo O3 will answer!

- Is there a gap?  
  \[ \mathcal{O}(10) \] binary BH detection

- Where is the lower edge of the gap?  
  \[ \mathcal{O}(100) \] binary BH detection

\[
\frac{dN}{dM_{\text{He}}} \propto M_{\text{He}}^{-2.35}
\]

\[ q \overset{\text{def}}{=} \frac{M_2}{M_1} \geq 0.5 \]

(motivated by LVC 2016)

\[
M_{\text{chirp}} \overset{\text{def}}{=} \frac{(M_1 M_2)^{3/5}}{(M_1 + M_2)^{1/5}} [M_{\odot}]\]
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\[ \Delta e = \frac{\Delta M}{M_1 + M_2 - \Delta M} \]
Two PPI in a binary

\[ \Delta e = \frac{\Delta M}{M_1 + M_2 - \Delta M} \]
Eccentricity distribution

\[ M_i \left( M_{\text{pre SN}}, M_{\text{BH}} \right) \left[ M_\odot \right] \]

\[ q = 1 \]

- 70 (50.3, 43.9)
- 82 (57.0, 37.3)
- 86 (59.2, 29.9)

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Take home points

• Uncertain wind mass loss rates influence the pre-SN core
  ⇒ systematic bias in SN initial conditions and outcome?

• The vast majority of binaries are disrupted
  ⇒ X-ray binaries and GW sources are exceptions

• Binarity leaves imprint on the ejected star

• “Widow” companions ejected constrain BH kicks

Simulations of Pulsational Pair Instability possible with MESA
including self-consistently dynamical evolution

• can modify binary orbit and remnant spin
  ⇒ Signature on gravitational wave signals?

• determines BH masses below PISN gap
Take home points

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Thank you!
Outline

Backup slides
Upper-limits in BH mass

$M_{\text{He}} = 48.5 \, M_{\odot}$

Infalling core

Outgoing pulse wave

Mass lost in previous pulses

velocity [$10^8 \text{cm s}^{-1}$]

$V_{\text{esc}}$

$0$

$-1$

$0$

Outgoing pulse wave

Infalling core

$M$ [$M_{\odot}$]

$0$

$5$

$10$

$15$

$20$

$25$

$30$

$35$

$40$

$45$

$50$

$0$

$5$

$10$

$15$

$20$

$25$

$30$

$35$

$40$

$45$

$50$
How many pulses?

- as a function of He core mass
Number of pulses

One pulse = One mass ejection

Renzo, Farmer et al., to be submitted
When do the pulsate?

- as a function of He core mass
Pulses timing

\[ \log_{10} \left( \frac{t_{\text{CC}} - t}{\text{yr}} \right) \]

\[ M_{\text{He}} \left( M_\odot \right) \]

Renzo, Farmer et al., to be submitted
Pulses timing

Log Time to core-collapse

\[ \log_{10}(t_{\text{core-collapse}} / \text{yr}) \]

Years-Months timescale

\( M_{\text{He}} \) [\( M_\odot \)]

Renzo, Farmer et al., to be submitted
How much mass is ejected per pulse?
How much mass is ejected in total?

- as a function of He core mass
Mass lost per pulse

\[ \Delta M_{\text{pulse}} [M_{\odot}] \]

\[ M_{\text{He}} [M_{\odot}] \]

Renzo, Farmer et al., to be submitted
Total mass lost

\[ \Delta M_{\text{total}} \quad [M_\odot] \]

\[ M_{\text{He}} \quad [M_\odot] \]

Renzo, Farmer et al., to be submitted
How fast are the ejected shells?

• as a function of He core mass
Center of mass velocity
Center of mass velocity

Progenitors of (some) SNIbn ?

\[ \langle v \rangle \, [\text{km s}^{-1}] \]

\[ M_{\text{He}} \, [M_{\odot}] \]

Renzo, Farmer et al., to be submitted
Can the mass shell collide?

Woosley et al. 07, Chen et al. 14, Woosley 17, Renzo, Farmer et al., to be submitted
Can the mass shells collide?

Distance to the star

\( \log_{10} R [\text{cm}] \)

\( \tau - \tau_{\text{CC}} \) [yr]

Time to core-collapse

No self-interaction or potential well

\( M_{\text{He}} = 40 M_\odot \)

Renzo, Farmer et al., to be submitted
Example: $40 M_{\odot}$ He core

![Graph showing time to core-collapse for a 40 $M_{\odot}$ He core.](image)

- $M_{\text{tot}}$ (blue line)
- $T_c$ (green line)

Log Time to core-collapse

Renzo, Farmer et al., to be submitted
Velocity distribution: Runaways

![Graph showing velocity distribution with probability on the y-axis and velocity difference $v_{\text{dis}}$ in $\text{km s}^{-1}$ on the x-axis. The graph includes multiple curves representing different data sets.]
Take home points:

- Walkaways outnumber the runaways by $\sim 10 \times$
- Binaries barely produce $v_{\text{dis}} \gtrsim 60 \text{ km s}^{-1}$
- All runaways from binaries are post-interaction objects

Renzo et al., submitted, arXiv:1804.09164
Velocity distribution: Walkaways

- Walkaways outnumber the runaways by \( \sim 10 \times \)
- Binaries barely produce \( v_{\text{dis}} \gtrsim 60 \text{ km s}^{-1} \)
- All runaways from binaries are post-interaction objects

Under-production of runaways because mass transfer widens the binaries and makes the secondary more massive
Example: $40 \, M_\odot$ He core with MESA

\[
\log_{10}\left\{ \left( \frac{t_{cc} - t}{\text{[yr]} \right) \right\}
\]

Log Time to core-collapse

Renzo, Farmer et al. (in prep.)
Spin down due to PPI ejecta

GW circularization

\( M_i \left( M_{\text{pre SN}}, M_{\text{BH}} \right) [M_\odot] \)

- Red: 70 (50.3, 43.9)
- Purple: 82 (57.0, 37.3)
- Orange: 86 (59.2, 29.9)

**Initial Conditions**

- \( f_{gw} = 10^{-4} \text{ Hz} \)
- \( f_{gw} = 10^{-3} \text{ Hz} \)
- \( f_{gw} = 10^{-2} \text{ Hz} \)

**Variables**

- \( 1 - F(e) \)
- \( t_m = 1.38 \text{ [Gyr]} \)

**Axes**

- X-axis: \( \log_{10} e \)
- Y-axis: Time