Explosions in massive binaries:

“widowed” stars and consequences for GW astronomy

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Why are massive stars important?

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

Nucleosynthesis & Chemical Evolution

Star Formation

Ionizing Radiation

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)
Masses in the Stellar Graveyard

in Solar Masses
Outline

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
  - Post-pulsations BH spins

Conclusions
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Methods: Population Synthesis

Fast ⇒ Allows statistical tests of the inputs & assumptions

- SN kicks
- Stellar Winds
- Population of disrupted binaries
- RLOF & Common Envelope
- Mass Transfer
- Tidal Interactions

Initial Distributions

Evolution (binary_c)

Izzard et al. '04, '06, '09; de Mink et al. '13
Binary disruption

Credits: ESO, L. Calçada, M. Kornmesser, S.E. de Mink
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

Renzo et al. 18, arXiv:1804.09164

- 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)
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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: $v$ emission and/or ejecta anisotropies

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

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

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A way to constrain BH kicks with *Gaia*

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

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

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A way to constrain BH kicks with *Gaia*

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

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

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

Renzo *et al.*, submitted, arXiv:1804.09164
Massive runaways mass function ($v \geq 30 \text{ km s}^{-1}$, $M \geq 7.5 \, M_\odot$)

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

- 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
  - ($\sigma_{\text{kick}} = 265 \text{ km s}^{-1}$, fiducial)
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Radiation dominated:

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

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

Woosley 2017,

Marchant, Renzo et al. arXiv:1810.13412,

Renzo, Farmer et al., to be submitted
$\Gamma_1 \overset{\text{def}}{=} \left( \frac{\partial \ln P}{\partial \ln \rho} \right)_s$

He core computed with MESA

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

$\langle E_{\gamma} \rangle < E_{\text{Fermi}}$

non rel. $e^\pm$

pressure support

$\langle E_{\gamma} \rangle < 2m_e c^2$

$\Gamma_1 < 4/3$
2. Softening of EOS triggers collapse
\[ \Gamma_1 < \frac{4}{3} \]

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

Thermal timescale
\[ \tau \propto \frac{G M_{He}^2}{R L_v}, \quad L_v \gg L \]

(Fraley 68)
1. Pair production
\[ \gamma \gamma \rightarrow e^+ e^- \]

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

3. Explosive (oxygen) ignition
2. Softening of EOS triggers collapse \( \Gamma_1 < \frac{4}{3} \)

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3. Explosive (oxygen) ignition

4a. Pulse with mass ejection

4b. PISN: complete disruption

Renzo, Farmer, et al., to be submitted
1. Pair production
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\[ \Gamma_1 < \frac{4}{3} \]
3. Explosive
(oxygen)
ignition
4a. Pulse with mass ejection
4b. PISN: complete disruption
5. \( \nu \)-cooling
and contraction
6. Entropy loss
and fuel depletion
stabilize the core
7. BH

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

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., to be submitted
The origin of very massive BHs

He core mass

$M_{CO} [M_\odot]$
The origin of very massive BHs

He core mass

$M_{\text{He}} [M_\odot]$ $M_{\text{CO}} [M_\odot]$ $M_{\text{BH}} [M_\odot]$
The origin of very massive BHs

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

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BH mass function

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

\[ q \geq 0.5 \]

(motivated by LVC 2016)

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

\( q \geq 0.5 \)

(motivated by LVC 2016)

\[ M_{\text{chirp}} \overset{\text{def}}{=} \frac{(M_1 M_2)^{3/5}}{(M_1 + M_2)^{1/5}} [M_\odot] \]
BH mass function

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

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

\[ q \geq 0.5 \]

(motivated by LVC 2016)

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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

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Spin down due to PPI ejecta

\[ a(M_f)/a(M_{\text{pre SN}}) \]

\[ M_i (M_{\text{pre SN}}) [M_{\odot}] \]

- 46 (35.8)
- 54 (40.8)
- 62 (45.6)
- 70 (50.3)
- 78 (54.8)
- 86 (59.2)

Keep the stars together

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Conclusions
Take home points

From population synthesis:

- **The vast majority of massive binaries are disrupted**
  ⇒ X-ray binaries and GW sources are exceptions
- **Binarity leaves imprint on the ejected star**
  ⇒ Spectroscopic followup of *Gaia* can distinguish them
- **“Widow” companions can constrain BH kicks**

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

- **determines BH masses below PISN gap**
  ⇒ LIGO/Virgo O3 will probe this
- **can modify BH spin**
  ⇒ Signature on gravitational wave signals?
- **can modify binary eccentricity**
  ⇒ eccentric binary BH from “isolated” binaries?

Renzo, Farmer *et al.*, to be submitted,
Marchant, Renzo, *et al.*, arXiv:1810.13412,
Farmer, Renzo, *et al.*, to be submitted
Upper-limits in BH mass

\[ M_{\text{He}} = 48.5 \, M_\odot \]

Outgoing pulse wave

\[ v_{\text{esc}} \]

Infalling core
How many pulses?

- as a function of He core mass
Number of pulses

One pulse = One mass ejection
When do the pulsate?

- as a function of He core mass
Pulses timing

\[ \log_{10}(t_{\text{CC}} - t)/[\text{yr}] \]
Pulses timing

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

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

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

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

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

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

Renzo, Farmer \textit{et al.}, to be submitted
Center of mass velocity

Progenitors of (some) SNIbн ?

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

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

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

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

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

Time to core-collapse

No self-interaction or potential well

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

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

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

Under-production of runaways because

mass transfer widens the binaries and makes the secondary more massive

- Walkaways outnumber the runaways by $\sim 10 \times$
- Binaries barely produce $v_{\text{dis}} \gtrsim 60 \text{ km s}^{-1}$
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Radiatively Driven Winds in One Slide

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

Problems: High Non-Linearity and Clumpiness
Clumpiness

Inhomogeneities:

\[ f_{cl} \overset{\text{def}}{=} \frac{\langle \rho^2 \rangle}{\langle \rho \rangle^2} \neq 1 \Rightarrow \dot{M} \neq 4\pi r^2 \rho v(r) \]
**Clumpiness**

**Risk:**
Possible overestimation of the wind mass loss rate

**Inhomogeneities:**

\[ f_{\text{cl}} \overset{\text{def}}{=} \frac{\langle \rho^2 \rangle}{\langle \rho \rangle^2} \neq 1 \Rightarrow \dot{M} = \eta 4\pi r^2 \rho v(r) \]
MESA grid varying \( \frac{dM}{dt} \)

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” \( (T_{\text{eff}} \geq 15 \ [kK]) \), “cool” \( (T_{\text{eff}} < 15 \ [kK]) \) and WR:

- Kudritzki et al. ’89; Vink et al. ’00, ’01;
- Van Loon et al. ’05; Nieuwenhuijzen et al. ’90;
- De Jager et al. ’88;
- Nugis & Lamers ’00; Hamann et al. ’98.
Impact on the final mass

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

$\eta \rightarrow$ largest uncertainty

$\frac{M}{M_{\text{ZAMS}}}$

$M_{\text{ZAMS}} \ [M_{\odot}]$

Renzo et al. '17
Impact on the final mass

Legend:

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

$\eta \rightarrow$ 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
“Explodability” & Compactness

\[ \xi M(t) \overset{\text{def}}{=} \frac{M/M_\odot}{R(M)/1000 \text{ km}} \]

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

not to scale!

\[ M = 2.5 M_\odot \]

\[ R(M) \]
Core structure at O depletion

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

Critical point:
Ne core/C shell burning

\[ \xi_{2.5} \leq 0 \]

Log time to O depletion

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

\( \eta = 1.0 \)
\( \eta = 0.33 \)
\( \eta = 0.1 \)

\( \text{V-dJ} \)
\( \text{K-vL} \)
\( \text{V-vL} \)
\( \text{V-NJ} \)
\( \text{K-NJ} \)
\( \text{K-dJ} \)

Renzo et al. '17
Post O burning evolution

Si shell burning →

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

Renzo et al. '17
Post O burning evolution

Anton Pannekoek Institute

Si shell burning →

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

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

Uncertainties in the wind impact the pre-SN core

Renzo et al. '17