Massive widowed stars:

Runaways and walkaways from binary disruptions


Mathieu Renzo
PhD in Amsterdam
What is a runaway star?

Observed velocity distribution for young ($\lesssim 50$ Myr) stars

Runaway fraction

O-type: $\sim 10 - 20\%$

from Tetzlaff et al. 11,

see also Zwicky 57, Blaauw 61, 93, Gies & Bolton 86, Leonard 91, Renzo et al. 18, submitted, arXiv:1804.09164
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Two ejection mechanisms

Dynamical interactions
- Extremely massive runaways in 30 Doradus

Binary disruption
- Velocity distribution of “widowed” companions
- BH kicks from massive runaway mass function
N-body interactions
(typically) least massive thrown out.

Binaries matter...

- (Binding) Energy reservoir
- Cross section $\propto a^2 \gg R_*$

Poveda et al., 1967

..but don’t necessarily leave imprints!
The most massive runaways known

- **R136**
  - $M = 137.8^{+27.5}_{-15.9} \, M_\odot$

- **VFTS682**
  - $M = 91.6^{+11.5}_{-10.5} \, M_\odot$

- **VFTS16**
  - $M = 97.6^{+22.2}_{-23.1} \, M_\odot$

- **VFTS72**
  - $M = 137.8^{+27.5}_{-15.9} \, M_\odot$

Renzo et al., submitted

Lennon et al., accepted, arXiv:1805.08277
The most massive runaways known

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\[ v_{2D} = 93 \pm 15 \text{ km s}^{-1} \]

\[ v_{3D} \simeq v_{2D} \]

\[ M = 91.6^{+11.5}_{-10.5} M_\odot \]

\[ v_{2D} = 80 \pm 11 \text{ km s}^{-1} \]

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The most massive runaways known

\[ M = 137.8^{+27.5}_{-15.9} M_\odot \]
\[ \nu_{2D} = 38 \pm 17 \text{ km s}^{-1} \]

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\[ \nu_{3D} \approx \nu_{2D} \]

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Binary disruption

Initial close binary

Most common evolutionary scenario for massive binaries
Most common evolutionary scenario for **massive binaries**
Binary disruption

Initial close binary

Orbit Widens

Stripped star + Accretor

Most common evolutionary scenario for massive binaries
Most common evolutionary scenario for **massive binaries**

- Initial close binary
- Orbit Widens
- Stripped star + Accretor
- Core Collapse & Disruption
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 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)

\[ v_{\text{dis}} \sim v_{\text{pre-SN}}^{\text{pre-SN}} \]
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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

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

Physically: \( \nu \) emission and/or ejecta anisotropies

Do BH receive kicks?

Credits: Ott, C. D., Drasco, S.
What I do: Population Synthesis

Fast $\Rightarrow$ Allows statistical tests of the inputs & assumptions

SN kicks
Stellar Winds
Population of disrupted binaries

Initial Distributions
RLOF & Common Envelope
Tidal Interactions
Mass Transfer

Evolution (binary_c)

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

Dynamical interactions
- Extremely massive runaways in 30 Doradus

Binary disruption
- Velocity distribution of “widowed” companions
- BH kicks from massive runaway mass function
Velocity distribution: Runaways
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.

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A way to constrain BH kicks

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

Mass of the runaway

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

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

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

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

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Mass of the runaway

Renzo et al., submitted, arXiv:1804.09164
Conclusions

Binary Disruption

- $86^{+11}_{-9}\%$ of binaries disrupted, most eject a slow walkaway
- Observed runaway fraction for O-type stars is $\times 10$ higher than binary populations can explain
- *Gaia* can constrain BH kicks using the mass distribution of massive runaways

Dynamical ejections (?)

- *Gaia* reveals the most massive runaways known (up to $\sim 150 M_\odot$)
- Extreme clusters can eject some of the most massive members
- Constraints on cluster formation and early dynamics
Backup slides
Two ejection mechanisms

Binary Supernova

- Ejects initially less massive star
- Requires SN kick
- Final $v \simeq v_{\text{orb}}^2$
- Leaves binary signature (fast rotation, He/N enhancement, lower apparent age)

Dynamical Ejection

- N-body interactions
- (Typically) least Massive thrown out

...Binaries are still important!

- (Binding) Energy reservoir
- Cross section $\propto a^2 \gg R_*^2$

but might not leave signature
Observations of stellar velocities

- Bow shocks
- Doppler shifts
- Proper motions (if distance known)

Diagram showing:
- Radial velocity
- Space velocity
- Transverse velocity
- Proper motion

Graph showing:
- Flux vs. Wavelength
Observations of stellar velocities

⇐ Bow shocks

Doppler shifts

⇒ Proper motions

(if distance known)

↓

Flux

Wavelength
Initial Distributions

Kroupa '01 (or Schneider et al., '18)

slope=-2.3 (or -1.9)

$M_1 \ [M_\odot]$  

$q = M_2 / M_1$

Maxwellian $\sigma_{v_{\text{kick}}} = 265 \text{ km s}^{-1}$ + Fallback rescaling

(from Fryer et al. '12)

Sana et al., '12

slope=-0.55

if $M_1 \geq 15M_\odot$

else flat

Hobbs et al. '05

Probability

$\log_{10}(P/\text{[days]})$

$P$
Star forming region velocity dispersion

\[ R_{15} = 26.8 \]

\[ R_{15}^{\text{SFH}} = 14.1 \]

\[ \geq 15 \, M_\odot \]

Convolved
Velocity distribution with lifetimes

Renzo et al., submitted, arXiv:1804.09164
Velocity distribution log-scale

\[ \log_{10}(v_{\text{dis}} / \text{km s}^{-1}) \]

- Runaways ⇒ 10^{-1}
- Walkaways ⇐ 10^{-1}

Probability \times 10^{-3}

Renzo et al., submitted, arXiv:1804.09164
Velocity distribution bound binaries

- NS + MS star
- BH + MS star

**Normalized Probability**

- fiducial ($\sigma_{kick} = 265 \text{ km s}^{-1}$)
- Double Maxwellian

**Cumulative Probability**

- no fallback downscaling

Renzo et al., submitted, arXiv:1804.09164
Velocity post-main sequence stars

Renzo et al., submitted, arXiv:1804.09164
pre-CC mass distribution

Renzo et al., submitted, arXiv:1804.09164
pre-CC separation distribution

\[ M_{2\,\text{pre-CC}} \geq 7.5 \, M_\odot \]

\[ M_{2\,\text{pre-CC}} \geq 15 \, M_\odot \]

all \( M_{2\,\text{pre-CC}} \)

\[ \log_{10}(a_{\text{pre-CC}}/R_\odot) \]
Unprojected spin distribution

\[ v_{\text{dis}} \text{ [km s}^{-1}\text{]} \]

\[ v_{\text{eq, dis}} \text{ [km s}^{-1}\text{]} \]

\[ M_{\text{dis}} \geq 7.5 M_\odot \]

\[ \log_{10}(P_{\text{dis}}) \]

% tot % Rw

Renzo et al., submitted, arXiv:1804.09164
How far do they get?

“Distance traveled”
(No potential well)

Renzo et al., submitted,
arXiv:1804.09164
Runaway fraction for O-type **too low**!

<table>
<thead>
<tr>
<th>Physical Assumptions</th>
<th>Parameter</th>
<th>value</th>
<th>( \mathcal{D} ) [%]</th>
<th>( f_{15}^{RW} ) [%]</th>
<th>( f_{15}^{WA} ) [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fiducial population</td>
<td>see Sec. 2</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Mass transfer efficiency</td>
<td>( \beta_{RLOF} )</td>
<td>0</td>
<td>86</td>
<td>0.3</td>
<td>1.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.5</td>
<td>87</td>
<td>1.2</td>
<td>8.6</td>
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<td></td>
<td></td>
<td>1</td>
<td>87</td>
<td>0.7</td>
<td>14.7</td>
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<tr>
<td>Angular momentum loss</td>
<td>( \gamma_{RLOF} )</td>
<td>0</td>
<td>85</td>
<td>0.2</td>
<td>7.3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>86</td>
<td>0.6</td>
<td>9.9</td>
</tr>
<tr>
<td>Common envelope efficiency</td>
<td>( \alpha_{CE} )</td>
<td>0.1</td>
<td>86</td>
<td>0.5</td>
<td>10.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10</td>
<td>84</td>
<td>0.5</td>
<td>10.0</td>
</tr>
<tr>
<td>Mass ratio for case A merger</td>
<td>( q_{crit, A} )</td>
<td>0.80</td>
<td>86</td>
<td>0.5</td>
<td>10.2</td>
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<td></td>
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<td>0.25</td>
<td>86</td>
<td>0.6</td>
<td>9.4</td>
</tr>
<tr>
<td>Mass ratio for case B merger</td>
<td>( q_{crit, B} )</td>
<td>1.0</td>
<td>89</td>
<td>0.0</td>
<td>5.0</td>
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<td>0.0</td>
<td>85</td>
<td>0.6</td>
<td>10.1</td>
</tr>
<tr>
<td>Natal kick velocity</td>
<td>( \sigma_{kick} )</td>
<td>0</td>
<td>16</td>
<td>–</td>
<td>0.0</td>
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<tr>
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<td></td>
<td>300</td>
<td>87</td>
<td>0.6</td>
<td>10.3</td>
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<tr>
<td></td>
<td></td>
<td>1000</td>
<td>91</td>
<td>1.2</td>
<td>11.2</td>
</tr>
<tr>
<td>Natal kick amplitude</td>
<td>( (\sigma_{kick}, f_b) )</td>
<td>(100, 0)</td>
<td>84</td>
<td>0.3</td>
<td>8.7</td>
</tr>
<tr>
<td>Double maxwellian with ( \sigma_{kick} = 30 \text{ km s}^{-1} ) for ( M_{NS} \leq 1.35 )</td>
<td></td>
<td></td>
<td>65</td>
<td>0.5</td>
<td>4.9</td>
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<tr>
<td>Restricted kick directions</td>
<td>( \alpha &lt; 10 \text{ deg} )</td>
<td></td>
<td>87</td>
<td>0.6</td>
<td>10.3</td>
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<tr>
<td></td>
<td>( \frac{\pi}{2} - \alpha &lt; 45 \text{ deg} )</td>
<td></td>
<td>86</td>
<td>0.5</td>
<td>10.0</td>
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<tr>
<td>Fallback fraction</td>
<td>( f_b )</td>
<td>0</td>
<td>97</td>
<td>1.5</td>
<td>12.1</td>
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<tr>
<td>Metallicity</td>
<td>( Z )</td>
<td>0.0002</td>
<td>77</td>
<td>2.6</td>
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<td>0.03</td>
<td>88</td>
<td>0.5</td>
<td>10.0</td>
</tr>
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</table>

Robust outcome (but less bad at low \( Z \))

\[
\begin{align*}
 f_{15}^{RW} & \overset{\text{def}}{=} \frac{\# \text{ runaways}}{\# \text{ stars}} \\
 f_{15}^{RW} & \sim 10 - 20\% \\
 & \sim \frac{2}{3} \text{ of runaways from binaries}
\end{align*}
\]

Hoogerwerf *et al.* '01

but see also Jilinski *et al.* '10

Renz *et al.*, submitted,

arXiv:1804.09164
VFTS682: Concordant Picture?

Large error bars compatible with no motion, but best values fit with expectations for dynamical ejection

Renzo et al., submitted
Why are they interesting?

Nucleosynthesis & Chemical Evolution

Star Formation

Ionizing Radiation

Supernovae

GW Astronomy

∼70% of O type stars are in close binaries
(e.g., Mason et al. '09, Sana & Evans '11, Sana et al. '12, Kiminki & Kobulnicky '12, Kobulnicky et al. '14, Almeida et al. '16)

∼10% of O type stars are runaways
($v \gtrsim 30 \text{ km s}^{-1}$)
(e.g., Blaauw '61, Gies '87, Stone '91, Tetzlaff et al. '11)
Do BH receive natal kicks?

- BH kicks
- Binary evolution

Spatial distribution of X-ray binaries

Massive (and WR) runaways

Disrupted binaries are “failed” GW sources!

(e.g., Repetto et al. '12,'15,'16, Mandel '16)

(Dray et al. '05)
Physics lessons...
...from disrupted binaries

- Orbital evolution ⇔ pre-SN period
- Mass transfer efficiency ⇔ pre-SN $M_2$
- Angular momentum loss ⇔ isotropic re-emission, circumbinary disk, etc.