Massive widowed stars:
Runaways and walkaways from binary disruptions

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NASA, JPL-Caltech, Spitzer Space Telescope
Why are they interesting?

- Nucleosynthesis & Chemical Evolution
- Star Formation
- Ionizing Radiation
- Supernovae
- GW Astronomy

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∼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)
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Preliminary:
∼ 20 walkaways for each O-type runaway
(e.g., Renzo et al., in prep, de Mink et al. '14)
Outline

How to measure stellar velocities?

How to generate widowed stars?

Methods: population synthesis

Preliminary results

Conclusions
Observations of stellar velocities

Bow shocks

Doppler shifts

Proper motions

(if distance known)

\[
\text{Radial velocity} \quad \text{Space velocity} \quad \text{Transverse velocity} \\
\text{Proper motion}
\]
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Binary disruption

Credits: ESO, L. Calçada, M. Kornmesser, S.E. de Mink
Spin up, pollution, and rejuvenation

The binary disruption shoots out the accretor

e.g., Packet '81, Cantiello et al. '07, de Mink et al. '13
What exactly disrupts the binary?

$\gtrsim 80\%$ 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)

$$v_{\text{post-SN}} \sim v_{\text{pre-SN}}$$
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\[ v_{2,\text{post-SN}} \approx v_{2,\text{pre-SN}} \approx v_{2,\text{orb}} \]
\( \nu \) emission and/or ejecta anisotropies
SN natal kick

do BH receive a kick?

$\nu$ emission and/or ejecta anisotropies

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

Fast ⇒ Allows statistical tests of the inputs & assumptions

- SN kicks
- Stellar Winds
- Initial Distributions
- Runaway Population
- RLOF & Common Envelope
- Tidal Interactions
- Mass Transfer

Izzard et al. '04, '06, '09; de Mink et al. '13
**Initial Distributions**

- **Kroupa '01**
  - Probability distribution of $M_1$ [M$_\odot$]
  - Slope = -2.3

- **flat**
  - Probability distribution of $q = M_2 / M_1$

- **Sana et al., '12**
  - Probability distribution of $\log_{10}(P/\text{[days]})$
  - Slope = -0.55
  - If $M_1 \geq 15M_\odot$, else flat

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

(From Fryer et al. '12)

- Probability distribution of NS kick [km s$^{-1}$]
  - Hobbs et al. '05
Velocity distribution: Runaways

Runaways ⇒

- All MS
- $M_{\text{dis}} \geq 7.5 \, M_\odot$
- $M_{\text{dis}} \geq 15 \, M_\odot$

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

0.00 0.01 0.02

30 40 50 60 70 80
Velocity distribution: Walkaways

For each runaway there are $\sim 20$ walkaways in the galaxy!
Velocity distribution: Walkaways

For each runaway there are $\sim 20$ walkaways in the galaxy!
Where do they die?

No potential well, $\sigma_{\text{kick}} = 265 \text{ km s}^{-1}$

for $M \geq 7.5 M_\odot$:

$\langle D \rangle = 128 \text{ pc}$

$\langle D_{\text{walk}} \rangle = 103 \text{ pc}$

$\langle D_{\text{run}} \rangle = 525 \text{ pc}$
(Massive) runaway mass function

BH $\Leftrightarrow M_{BH} \geq 2.5 \, M_\odot$, Only $v \geq 30 \, \text{km} \, \text{s}^{-1}$ and $M_{\text{dis}} \geq 7.5 \, M_\odot$
(Massive) runaway mass function

BH $\leftrightarrow M_{\text{BH}} \geq 2.5 \, M_\odot$, Only $v \geq 30 \, \text{km s}^{-1}$ and $M_{\text{dis}} \geq 7.5 \, M_\odot$
Anton Pannekoek
Institute

(Massive) runaway mass function

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

\( \text{BH kick}=\text{NS kick} \) (no fallback)

\( \text{BH momentum kick} \) (fiducial)

No BH kick

BH \( \Leftrightarrow M_{\text{BH}} \geq 2.5 M_\odot \), Only \( v \geq 30 \text{ km s}^{-1} \) and \( M_{\text{dis}} \geq 7.5 M_\odot \)
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How to measure stellar velocities?
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Conclusions

∼ 80% of binaries disrupted by first SN

Massive walk/runaways stars...

(whatever their final velocity)

- ...carry info on previous binary evolution
- ...can be used to learn about companion explosion
- ...enhance the massive stars feedback
Conclusions

\[ \sim 80\% \text{ of binaries disrupted by first SN} \]

Massive walk/runaways stars...

(Regardless of their final velocity)

- ...carry info on previous binary evolution
- ...can be used to learn about companion explosion
- ...enhance the massive stars feedback

Thank you!
Backup slides
Where do they die?

“Distance traveled”

No potential well, $\sigma_{\text{kick}} = 265 \text{ km s}^{-1}$
- **Unbinding Matter**
  (e.g., Blaauw '61)

- **SN Natal Kick**
  (e.g., Shklovskii '70, Janka '16)

- **Ejecta Impact**
  (e.g., Wheeler *et al.* '75, Tauris & Takens '98, Liu *et al.* '15)

\[ v_{RW} \approx v_{orb}^2 \]
Mass-rotation correlation 1/2

![Diagram showing a correlation between mass and rotation rate. The x-axis represents mass ($M_{\text{RW}}$ in $M_\odot$) and the y-axis represents rotational velocity ($v_{\text{eq} \sin(i)}$ in km s$^{-1}$). Colors indicate log of rotational velocity ($\log_{10}(P_{\text{RW}})$).]
Spin Down: Winds

First SN explosion & Disruption

$M_{ZAMS}^1 = 25 M_\odot$, $M_{ZAMS}^2 = 16 M_\odot$, $P_{ZAMS} = 100$ days
Initial Rotational Velocities

Rotation @ $t=0$ from O. Ramirez-Agudelo et al. ’15
**SN natal kicks**

**Orbit** from Tauris & Takens ’98

**Fallback** from Fryer *et al.* ’12

(Rapid SN mechanism)

\[
\begin{align*}
M_{fb} &= 0.2 \, M_\odot \\
M_{fb} &= 0.286 M_{CO} - 0.514 \, M_\odot \\
f_{fb} &= 1.0 \\
f_{fb} &= a_1 M_{CO} + b_1 \\
f_{fb} &= 1.0
\end{align*}
\]

\[
\begin{align*}
M_{CO} &< 2.5 \, M_\odot \\
2.5 \, M_\odot &\leq M_{CO} < 6.0 \, M_\odot \\
6.0 \, M_\odot &\leq M_{CO} < 7.0 \, M_\odot \\
7.0 \, M_\odot &\leq M_{CO} < 11.0 \, M_\odot \\
M_{CO} &\geq 11.0 \, M_\odot
\end{align*}
\]

**Ejecta impact** from Liu *et al.* ’15

Fig. 2. Geometry of the orbital plane of a disrupted system \((e > 1, \ a < 0)\) after an asymmetric supernova explosion. The reference frame is fixed on the companion star (C).
$20 \, M_\odot + 15 \, M_\odot$ on $P_{\text{ZAMS}} = 100$ days $\Rightarrow v_2^{\text{pre-SN}} \simeq 12.55 \, \text{km s}^{-1}$
SN kick directions 2/2

\[ 20 M_\odot + 15 M_\odot \text{ on } P_{ZAMS} = 100 \text{ days } \Rightarrow v_2^{\text{pre-SN}} \approx 12.55 \text{ km s}^{-1} \]
N-body interactions

least massive thrown out

...binaries matter

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

Poveda et al., 1967