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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∼10% of O type stars are runaways

\( (v \gtrsim 30 \text{ km s}^{-1}) \)

(e.g., Blaauw '61, Gies '87, Stone '91)

∼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)
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Preliminary:

∼20 walkaways formed for each O-type runaway

(e.g., Renzo et al., in prep, de Mink et al. '14)
Astrophysical implications...
...of disrupting binaries

- Feedback

- “Binarity” hidden in single stars

- Massive Star Formation
Astrophysical implications...
...of disrupting binaries

- Enhancement of massive stars feedback
  - Larger volume
  - Spatial spread of CCSN
    (e.g., Conroy & Kratter '12)
  - Increase in ionizing radiation $f_{\text{esc}}$
    (e.g., Kimm & Cen '14)

- Feedback
- "Binarity" hidden in single stars
- Massive Star Formation
• Feedback

• “Binarity” hidden in single stars

• Massive Star Formation

• Contamination of field with binary products
  - Are “single” stars really single?
  - Have they always been?
Astrophysical implications...
...of disrupting binaries

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- “Binarity” hidden in single stars
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- Massive star formation
  - are isolated massive stars formed “in situ”?

(e.g., Bestenlehner et al. ’11, Gavramadze et al. ’12)
Outline

Introduction

Astrophysical implications

How to make fast stars?
- Dynamical ejection from cluster
- Disruption of binaries

Methods: population synthesis

Preliminary results
- O-type runaways in 30 Doradus
- Walkaways in the Milky Way

Conclusions
Binary disruption

Initial close binary
Binary disruption

Initial close binary → Orbit Widens
Binary disruption

Initial close binary

Orbit Widens

Stripped star + Accretor
Binary disruption

Initial close binary

Orbit Widens

Stripped star + Accretor

Core Collapse & Disruption
Spin up, pollution, and rejuvenation

Binary interactions modify the star to be ejected

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

\[ \sim 80\% \text{ of binaries are disrupted} \]

- 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)

\[ v_{2,\text{post-SN}} \sim v_{2,\text{pre-SN},\text{orb}} \]
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What I do: Population Synthesis

Fast → Allows statistical tests of the inputs & assumptions

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

Izzard et al. ’04, ’06, ’09; de Mink et al. ’13
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O-type runaways

Largest homogeneous sample available to date

"Projected rotational velocity" vs "Line of sight velocity"

Sana et al., VFTS collaboration, in prep.
O-type runaways

Largest homogeneous sample available to date

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O-type runaways

"Projected rotational velocity"

$\log_{10}(\text{Number density})$
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How to measure stellar velocities?

Line of sight velocity: Doppler shifts

Transverse velocity: Proper motions
(if distance known)
Gaia will give proper motions & distances
Velocity distribution: Runaways
• For each runaway there are $\sim 20$ walkaways in the galaxy
• All runaways have accreted mass from a companion
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- All runaways have accreted mass from a companion
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Conclusions

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

Massive walk/runaways stars...

(Regardless of their final velocity)

- ...“pollute” the field with binary products
- ...carry info on previous binary evolution
- ...can be used to learn about companion explosion
- ...enhance the massive stars feedback
Conclusions

\(~ 80\% \text{ of binaries disrupted by first SN} ~\)

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Thank you!
Backup slides
Where do they die?

“Distance traveled”

No potential well, $\sigma_{\text{kick}} = 265 \text{ km s}^{-1}$
30 Doradus Star Formation History

- lookback time $t_{lb}$ [Myr]

stellar age $\equiv |t_{lb}|$

Extended to constant SFH
Initial Rotational Velocities

Rotation @ t=0 from O. Ramirez-Agudelo et al. ’15
Spin Down: Winds

- \( v_{\text{eq}} \) \([\text{km s}^{-1}]\)
- \( M_1^{\text{ZAMS}} = 25 M_\odot \)
- \( M_2^{\text{ZAMS}} = 16 M_\odot \)
- \( P_{\text{ZAMS}} = 100 \text{ days} \)

First SN explosion & Disruption
Properties of the RWs in 30 Dor

Line of Sight Velocities

Rotational Velocities

Credits: H. Sana et al. (in prep.)

Soon proper motions!

(Lennon et al. in prep.)
SN natal kicks

**Orbit** from Tauris & Takens ’98

**Fallback** from Fryer *et al.* ’12

(Rapid SN mechanism)

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

\[
2.5 \, M_\odot \leq M_{CO} < 6.0 \, M_\odot \\
6.0 \, M_\odot \leq M_{CO} < 7.0 \, M_\odot \\
7.0 \, M_\odot \leq M_{CO} < 11.0 \, M_\odot \\
M_{CO} \geq 11.0 \, M_\odot
\]

**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).
Anton Pannekoek Institute

Binary Disruption

- 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)

\[ v_{RW} \simeq v_{2}^{orb} \]
**Physics lessons...**

**...from disrupted binaries**

- BH kicks
- Binary evolution

**Do BH receive natal kicks?**

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)
Constraints on binary physics

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

- BH kicks
- Binary evolution
Mass-rotation correlation

Runaways only

\( v_{eq\sin(i)} \text{ [km s}^{-1}\text{]} \)

\( M_{RW} \text{ [}\, M_{\odot}\text{]} \)

\( \log_{10}(P_{RW}) \)
Mass-rotation correlation

Runaways only
Mass-rotation correlation

Runaways only

$v \simeq 78 \text{ km s}^{-1}$
Where do they die?

iZw18

Credits: ESA/Hubble & Nasa, A. Aloisi
Where do they die?

for $M \geq 7.5 M_\odot$:

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

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Where do they die?

for $M \geq 7.5 \, M_\odot$:

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

$\langle D_{\text{run}} \rangle = 525 \, \text{pc}$

iZw18

Credits: ESA/Hubble & Nasa, A. Aloisi
Where do they die?

for $M \geq 7.5 \, M_\odot$:

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

\langle D_{\text{run}} \rangle = 525 \text{ pc}

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

Credits: ESA/Hubble & Nasa, A. Aloisi
How to test BH kick physics?

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

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

\[ \sigma_{\text{kick}} = 100 \text{ km s}^{-1} \]
(no fallback)

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

\[ \sigma_{\text{kick}} = 100 \text{ km s}^{-1} \]
(no fallback)

BH kick=NS kick

BH momentum kick
(fiducial)

BH \iff \ M_{\text{BH}} \geq 2.5 M_{\odot}, \text{ Only } v \geq 30 \text{ km s}^{-1} \text{ and } M_{\text{dis}} \geq 7.5 M_{\odot}
SN natal kick

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

Credits: Ott, C. D., Drasco, S.
Where do they die?

“Distance traveled”

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

- Kroupa '01 (or Schneider et al., in prep.)
  - Distribution of $M_1 [M_\odot]$
  - Probability
  - Slope $=-2.3$ (or $-1.9$)

- Flat distribution for $q = M_2 / M_1$

- Sana et al., '12
  - 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)

- Distribution of NS kick [km s$^{-1}$]

Hobbs et al. '05
N-body interactions

least massive thrown out

...binaries matter

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

Poveda et al., 1967