Massive widowed stars: Runaways and walkaways from binary disruptions

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Why are they interesting?

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

Star Formation

Ionizing Radiation

Supernovae

GW Astronomy

\( \sim 70\% \) 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)

\( \sim 10\% \) 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:
\[\sim 20 \text{ walkaways for each O-type runaway} \]
(e.g., Renzo et al., in prep, de Mink et al. '14)
Outline

How to measure stellar velocities?
Astrophysical implications

How to make fast stars?
  • Dynamical ejection
  • Binary disruption

Methods: population synthesis

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

Conclusions
Observations of stellar velocities

↔ Bow shocks

Doppler shifts

⇒ Proper motions
(if distance known)

↓

Radial velocity

Object

Space velocity

Transverse velocity

Proper motion

Sun

d

μ

Flux

Wavelength
Gaia will give proper motions & distances
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Astrophysical implications...
...of disrupting binaries

- Feedback
- Field contamination
- Massive Star Formation
- LBV
Astrophysical implications... 
...of disrupting binaries

- **Enhancement of massive stars feedback**
  - Larger volume
  - Spatial spread of CCSN
    (e.g., Conroy & Kratter '12)
  - $\sim 20\%$ increase in $f_{\text{esc}}$
    (e.g., Kimm & Cen '14)
Astrophysical implications...  
...of disrupting binaries

- Feedback
- Field contamination
- Massive Star Formation
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- Contamination of field with binary products
  - Are “single” stars really single?
  - Have they always been?
Astrophysical implications...  
...of disrupting binaries

- Feedback
- Field contamination
- Massive Star Formation
- LBV

- Massive star formation
  - are isolated massive stars formed “in situ”?  
  (e.g., Gavramidze et al. ’12)
Astrophysical implications...  
...of disrupting binaries

- **LBV phenomenon**
  - Do LBV require binarity?

- Feedback
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"Conti scenario"

(Fig. adapted from Douglas et al., '10)

(e.g., Conti, '75, Maeder & Conti '94)
Astrophysical implications...  
...of disrupting binaries

- **LBV phenomenon**
  - Do LBV require binarity?  
    (e.g., Smith & Tombleson '15, Smith '16, Aghakhanlootakanloo et al. '17)

- **Feedback**
- **Field contamination**
- **Massive Star Formation**
- **LBV**
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N-body interactions

least massive thrown out

...binaries matter

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

Poveda et al., 1967
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?

$\geq 80\%$ 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)

$$v_{2,\text{post-SN}} \approx v_{2,\text{pre-SN},\text{orb}}$$
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\[ v_{\text{post-SN}} \approx v_{\text{pre-SN,orb}} \]
SN natal kick

$\nu$ emission and/or ejecta anisotropies

Credits: Ott, C. D., Drasco, S.
(potential) Physics lessons...
...from disrupted binaries

- BH kicks
- Binary evolution

Do BH receive natal kicks?

Spatial distribution of X-ray binaries
(e.g., Repetto et al. '12,'15,'16, Mandel '16)

Massive (and WR) runaways
(Dray et al. '05)

Disrupted binaries are “failed” GW sources!

[Diagram showing BH inspiral, merger, and ringdown with strain plots and numerical relativity comparisons]
 Constraints on binary physics

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

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

Kroupa '01 (or Schneider et al., in prep.)

slope=-2.3 (or -1.9)

Flat

Sana et al., '12

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)

Hobbs et al. '05

Hobbs et al. '05
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Pros:

- Young region
- homogeneous $Z = Z_{\text{LMC}}$
- Multi-epoch spectroscopic coverage complete at $m_v \lesssim 17$

(VFTS, Evans et al. '11)

Cons:

- Young Massive clusters
“Rotational velocity” $v_{\text{rot}} \sin(i)$ [km s$^{-1}$] vs. “Line of sight velocity” $v_{\text{dis}}$ [km s$^{-1}$].

Largest homogeneous sample available to date

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

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O-type runaways

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

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

\[ P_{\text{dis}} \times 10^{-7} \]

\% tot \% Run

\% tot \% Run

VFTS sample

\[ t = 0 \, \text{Myr} \]
Mass-rotation correlation

Runaways only

\( \nu_{\text{eq, sin}(i)} \) [km s\(^{-1}\)] vs \( M_{\text{RW}} \) [\( M_\odot \)]

Color scale: \( \log_{10}(P_{\text{RW}}) \)

Values range from 0 to 700 with error bars indicating variability.
Mass-rotation correlation

Runaways only

\[ v \approx 78 \text{ km s}^{-1} \]
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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?

"Distance traveled"

No potential well, $\sigma_{\text{kick}} = 265$ 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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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 $M \geq 7.5 \, M_\odot$:

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

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

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

iZw18

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

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

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(Massive) runaway mass function

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

BH kick=NS kick (no fallback)

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

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% of binaries disrupted by first SN

Massive walk/runaways stars...
(whatever their final velocity)

- ...“pollute” the field with binary products
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- ...enhance the massive stars feedback

Thank you!
Backup slides
Where do they die?

Cumulative fraction

$log_{10}(\text{max}(D) / \text{[pc]})$

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

First SN explosion & Disruption

$M_{1}^{ZAMS} = 25 \, M_{\odot}$,

$M_{2}^{ZAMS} = 16 \, M_{\odot}$,

$p^{ZAMS} = 100 \, \text{days}$
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)

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

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

**Ejecta impact** from Liu et al. ’15

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**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).
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)

\[ v_{RW} \approx v_{orb}^2 \]