The impact of mass loss on the final structure and fate of massive stars

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NASA, JPL-Caltech, Spitzer Space Telescope
Why are massive stars important?

- Nucleosynthesis & Chemical Evolution
- Star Formation
- Ionizing Radiation
- Supernovae
- GW Astronomy
Why is their mass loss important?

Nucleosynthesis & Chemical Evolution

Star Formation

Ionizing Radiation

Supernovae

GW Astronomy

Mass loss for the environment:
- Pollution of ISM
- Tailoring of CSM
- Trigger for Star Formation

Mass loss for the star:
- Evolutionary Timescales
- Appearance & Classification (e.g. WR)
- Light Curve and Explosion Spectrum
- Final Fate: BH, NS or WD?
The “classical” picture

adapted from M. Weiss/NASA/CXC
How do massive stars lose mass?

**Stellar winds**
- Line driving mechanism
- Algorithmic treatment

**Impact on:**
- Final mass
- Core structure

**Conclusions**
- Take home points
Possible Mass Loss Mechanisms

Radiative Driving

\[ \downarrow \]

Stellar Winds

Figure: Betelgeuse
Possible Mass Loss Mechanisms

Dynamical Instabilities

\[ \downarrow \]

LBVs, Impulsive Mass Loss,
Pulsations,
Super-Eddington Winds

Figure: $\eta$ Carinae.
Possible Mass Loss Mechanisms

Binary interactions

\[ \Downarrow \]

Roche Lobe Overflow, Common Envelope, Fast rotation, Mergers

Figure: Artist Impression

(ESO/L. Calçada/M. Kornmesser/S.E. de Mink)
Possible Mass Loss Mechanisms

Binary interactions

Roche Lobe Overflow, Common Envelope, Fast rotation, Mergers

Figure: Artist Impression

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Mass loss is dynamical...

... but stellar evolution codes assume hydrostatic equilibrium:

\[ \frac{dP}{dr} = -\frac{Gm(r)\rho}{r^2} \]

Open question: Which dominates in term of total mass lost?
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Radiatively Driven Winds in One Slide

\[ \Delta p = \frac{\hbar}{c} \left( v_i \cos(\theta_i) - v_f \cos(\theta_f) \right) \]

Problems: High Non-Linearity and Clumpiness
Inhomogeneities:

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

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Risk:

Possible overestimation of the wind mass loss rate
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Mass loss in MESA

(Semi–)Empirical parametric models.

Efficiency factor:
\[ \dot{M}(L, T_{\text{eff}}, Z, R, M, ...) \]
\[ \downarrow \]
\[ \eta \dot{M}(L, T_{\text{eff}}, Z, R, M, ...) \]

\[ \eta \] is a free parameter:
\[ \eta \in [0, +\infty) \]

Figure: from N. Smith 2014, ARA&A, 52, 487
Combination of algorithms

\[ \log_{10}\left( \frac{L}{L_\odot} \right) \]

Hot wind

Cool wind

\[ \log_{10}\left( \frac{T_{\text{eff}}}{[\text{K}]} \right) \]

WR wind \( \Leftrightarrow X_s < 0.4 \)

\[ 15M_\odot, Z_\odot \]
Grid of $Z_\odot \simeq 0.019$, non-rotating stellar models:

- Initial mass:
  \[ M_{\text{ZAMS}} = \{15, 20, 25, 30, 35\} \ M_\odot; \]

- Efficiency:
  \[ \eta = \{1, \frac{1}{3}, \frac{1}{10}\} ; \]

- 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.
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Wind mass loss history

\[
M_{\text{ZAMS}} = 15 M_\odot
\]

\( t \) [Myr]

\( M \) \([M_\odot]\)

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

VdJNL, KvLNL, VvLNL, VNJNL, KNJNL, KdJNL

Renzo et al., in prep.
Wind mass loss history

$M_{\text{ZAMS}} = 15M_\odot$

$\eta = 1.0$
$\eta = 0.33$
$\eta = 0.1$
VdJNL
KvLNL
VvLNL
VNJNL
KNJNL
KdJNL

Renzo et al., in prep.
Impact on the final mass

\[
\frac{M}{M_{\text{ZAMS}}} \text{ vs. } M_{\text{ZAMS}} [M_{\odot}]
\]

**Legend:**
- \( \eta = 0.1 \)
- \( \eta = 0.33 \)
- \( \eta = 1.0 \)

Renzo et al., in prep.
Impact on the final mass

Impossible to map: $M_f \equiv M_f(M_{ZAMS})$

Just because of winds!

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

$\eta \rightarrow$ largest uncertainty

Renzo et al., in prep.
Impact on the final mass

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Legend:
- • \( \eta = 0.1 \)
- • \( \eta = 0.33 \)
- + \( \eta = 1.0 \)

\( \eta \rightarrow \) largest uncertainty

Renzo et al., in prep.
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“Explodability” & Compactness

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

- “Large” \( \xi_{2.5} \Rightarrow \text{harder to explode} \Rightarrow \text{BH formation} 
- “Small” \( \xi_{2.5} \Rightarrow \text{easier to explode} \Rightarrow \text{NS formation} 

(e.g. O’Connor & Ott 2011, Ugliano et al. 2012, Sukhbold & Woosley 2014)

\[ M = 2.5 M_\odot \]

not to scale!
\[ M_{\text{ZAMS}} = 25 \, M_\odot \]  \textbf{MESA} models

Critical point: Ne core burning/C shell burning

Renzo et al., in prep.
\(\xi_{2.5} @ O\) depletion

\[\begin{array}{cccc}
0.250 & 0.240 & 0.230 & 0.220 \\
0.210 & 0.200 & 0.190 & 0.180 \\
0.170 & 0.160 & 0.150 & 0.140 \\
\end{array}\]

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

Renzo et al., in prep.
\( \zeta_{2.5} @ \) Oxygen Depletion

Legend:
- \( \bullet \) \( \eta = 0.1 \)
- \( \times \) \( \eta = 0.33 \)
- \( + \) \( \eta = 1.0 \)

Post O burning evolution \( \downarrow \)
Core contraction \( \downarrow \)
Amplification of the differences.

Renzo et al., in prep.
Computing Advanced Burning Stages

- Initially small effect ⇒ $N_{\text{zones}} \gtrsim 20\,000$;
- Complex nuclear burning ⇒ $N_{\text{iso}} \gtrsim 200$;

SurfSara’s Cartesius Computer.
Post O burning evolution

Si shell burning →

Renzo et al., in prep.
Oscillations

Fuel ignition in (partially) degenerate environment

\[ \log_{10}(\frac{L_{\nu}}{L_\odot}) = \log_{10}(\frac{(t_{\text{pre-SN}} - t)/[\text{yr}])}{\xi_{2.5}}) \]

- Red: nuclear
- Purple: cooling
- Dotted: total

Renzo et al., in prep.
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Take home points

Uncertainties in stellar winds:

- pre-SN mass $\Rightarrow$ no $M_f \equiv M_f(M_{\text{ZAMS}})$ map;
- core structure $\Rightarrow$ “explodability” & remnant.
- stellar evolution is not done yet!
Take home points

Uncertainties in stellar winds:

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Thank you!
Backup slides
Supernova Taxonomy

Type I
- Si
  - No Si
    - Type Ia
    - Type Ic
  - No Si
- Type Ib

Type II
- Early
  - H
    - Line profiles
    - Light curve
    - Type II
  - No H
    - IIL
    - IIP
    - Type II
  - Early
    - IIb

Back
Mass Transfer in Binaries
**MESA nearly super-Eddington Regime**

\[
L_{\text{Edd}} \overset{\text{def}}{=} \frac{4\pi GM(R)c}{\kappa(r)}, \quad \frac{dP_{\text{gas}}}{dr} = \frac{dP_{\text{rad}}}{dr} \left[ \frac{L_{\text{Edd}}}{L_{\text{rad}}} - 1 \right]
\]

\[
\log_{10}(T/\text{[K]}) \quad \kappa \quad \log_{10}\left(\frac{\rho}{T_6^3}\right) = -5
\]

- Z=0.02
- Z=0.01
- Z=0.004
- Z=0.001
- Z=0.0001

**OPAL: X = 0.7, log(\rho/T_6^3) = -5**

- a) 70 M_\odot, T_{\text{eff}} = 5000 K
- b) 2.31
- c) 2.7
- d) 1000 1100 1200 1300

\[M_{\text{ZAMS}} \gtrsim 20M_\odot \Rightarrow \text{insufficient } F_{\text{MLT conv}}\]

**MLT++:**

\[\nabla_T - \nabla_{\text{ad}} \rightarrow \alpha_{\nabla} f_{\nabla}(\nabla_T - \nabla_{\text{ad}})\]

\[\alpha_{\nabla} \equiv \alpha_{\nabla}(\beta, \Gamma_{\text{Edd}}), \quad f_{\nabla} \ll 1\]
Wind Observational Diagnostics

- P Cygni line profiles
- Optical and near UV lines (e.g. Hα)
- Radio and IR continuum excess
- IR spectrum of molecules (e.g. CO)
- Maser lines (for low density winds)

Assumptions commonly needed:

- Velocity structure: \( \nu(r) \approx \left( 1 - \frac{r}{R_\ast} \right)^\beta \) with \( \beta \approx 1 \)
- Chemical composition and ionization fraction
- Spherical symmetry: \( \dot{M} = 4\pi r^2 \rho \nu(r) \)
- Steadiness and (often) homogeneity

\( \dot{M} \) derived from fit of (a few) spectral lines. No theoretical guaranties coefficients are constant.
Observational Definition:

**Based on spectral features indicating a Strong Wind:**
- Hydrogen Depletion ($\neq$ Lack of Hydrogen)
- Broad Emission Lines
- Steep Velocity Gradients

Sub-categories: WN, WC, WO, WNL, etc.

**Computational Definition (MESA):**
- $X_s < 0.4$

Impossible to distinguish sub-categories without spectra!
Evolution of a Massive Star in one Slide

- Back

\[
\log_{10}(L/L_\odot) \quad \text{vs.} \quad \log_{10}(T_{\text{eff}}/[K])
\]

- MS \( \Delta t_{\text{MS}} \sim 1.3 \cdot 10^8 \) yr
- OC \( \Delta t_{\text{OC}} \sim 7.9 \cdot 10^5 \) yr
- SGB \( \Delta t_{\text{SGB}} \sim 1.8 \cdot 10^5 \) yr
- RSG \( \Delta t_{\text{RSG}} \sim 1.2 \cdot 10^7 \) yr

- \( M = 15M_\odot, Z = Z_\odot \)
Evolution of a Massive Star in one Slide

Back
Evolution of a Massive Star in one Slide

\[ \log_{10}\left( \frac{T_{\text{eff}}}{[K]} \right) \]

\[ \log_{10}\left( \frac{L}{L_{\odot}} \right) \]

\[ M = 15M_{\odot}, \ Z = Z_{\odot} \]

\[ \Delta t_{\text{OC}} \sim 7.9 \cdot 10^5 \text{ yr} \]

\[ \Delta t_{\text{SGB}} \sim 1.8 \cdot 10^5 \text{ yr} \]

\[ \Delta t_{\text{RSG}} \sim 1.2 \cdot 10^7 \text{ yr} \]

\[ \Delta t_{\text{MS}} \sim 1.3 \cdot 10^8 \text{ yr} \]

Vink et al., de Jager et al.
Evolution of a Massive Star in one Slide

Back
P Cygni Line Profiles

- Blue shifted Absorption Component
- Red shifted Emission Component
- Broadening from scattering into the line of sight

\[ \dot{M} = 4\pi \rho v(r) \]

Assuming:
- Chemical composition
- Velocity Structure

the fit of the line profile gives \( \rho \)

Figure: 34 Cyg or P Cygni, first star to show the eponymous profile.