Systematic Study of Mass Loss in the Evolution of Massive Stars

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Hertzsprung-Russell Diagram(s)

Observational HR
- Snapshot of stellar populations \( (t = \text{const.}) \)
- Systematic \textbf{and} random errors
**Observational HR**
- Snapshot of stellar populations \((t = \text{const.})\)
- Systematic **and** random errors

**Theoretical HR**
- Evolutionary tracks from models (evolving in \(t\))
- Control over the parameters
- Possibility of Systematic Errors
Outline

Introduction

• Importance of Massive Stars
• How do they lose mass?

Stellar Winds

• Outline of the Theory
• Methods
• Results: Amplitude of the Uncertainty
• Results: Blue Loops in $15M_\odot$ models

Impulsive Mass Loss Events

• Motivations for This Study
• Methods
• Results: Wind + Impulsive Mass Loss
• Results: pre-SN Stripped Structures

Conclusions
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Why are Massive Stars Important?

\[ M_{\text{ZAMS}} \gtrsim 8 - 10 M_\odot \]

- Nucleosynthesis
- Chemical Evolution of Galaxies
- Effects on Star Formation
- Re-ionization Epoch
- Observations of Farthest Galaxies
- Catastrophic Events
Mass Loss – Why does it Matter...

... for the environment of the stars?

- Pollution of the InterStellar Medium (ISM)
- Tailoring of the CircumStellar Material (CSM)
- Effects on the Star Formation

... for the stellar structure?

- Evolutionary Timescales
- Final Fate (BH, NS or WD?)
- Light Curve and Explosion Spectrum
- Appearance: CSM and Wind Features (e.g. WR)
- Role in the Solution of the RSG Problem?
Possible Mass Loss Mechanisms

Radiative Driving

\[ \downarrow \]

Stellar Winds

Dynamical Instabilities

\[ \downarrow \]

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

Binary interactions

\[ \downarrow \]

Roche Lobe OverFlows (RLOF)

Figure: η Carinae.
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Radiatively Driven Winds in One Slide

\[ \Delta p = \frac{h}{c} \left( \nu_i \cos(\theta_i) - \nu_f \cos(\theta_f) \right) \]

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

Problems: High Non-Linearity and Clumpiness:
Radiatively Driven Winds in One Slide

\[ \Delta p = h c (\nu_i \cos(\theta_i) - \nu_f \cos(\theta_f)) \]

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

Risk:
Possible Overestimation of the Wind Mass Loss Rate

Problems: High Non-Linearity and Clumpiness:
(Semi–)Empirical parametric models. Uncertainties encapsulated in efficiency factor:
\[ \dot{M}(L, T_{\text{eff}}, Z, R, M, \ldots) \]
\[ \Rightarrow \eta \dot{M}(L, T_{\text{eff}}, Z, R, M, \ldots) \]
\[ \eta \text{ is a free parameter: } \eta \in [0, +\infty) \]

Figure: From Smith 2014, ARA&A, 52, 487S
Different $dM/dt$ algorithms with MESA

Grid of $Z_\odot \sim 0.019$, non-rotating stellar models:

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

- Efficiency:
  
  \[ \eta \equiv \sqrt{f_{\text{cl}}} = \{1, \frac{1}{3}, \frac{1}{10}\} ; \]

- Different combinations of wind mass loss rates for “hot” ($T_{\text{eff}} \geq 15 \, [\text{kK}]$), “cool” ($T_{\text{eff}} < 15 \, [\text{kK}]$) and WR stars:
  
  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.
Results: Relative Final Mass

$\frac{MO_{\text{dep}}}{M_{\text{ZAMS}}}$

$M_{\text{ZAMS}} [M_\odot]$

Diamonds $\Leftrightarrow \eta = 1.0$, Squares $\Leftrightarrow \eta = 0.33$, Circles $\Leftrightarrow \eta = 0.1$. 

$\eta$ is a parameter representing the efficiency or some characteristic of the mass loss process.
$M(t)$ for $M_{ZAMS} = 15M_{\odot}$ with MESA

$T_{AMS}$

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

- Blue line: Vink et al., de Jager et al.
- Yellow line: Kudritzki et al., Nieuwenhuijzen et al.
- Red line: Kudritzki et al., de Jager et al.
- Green line: Vink et al., Nieuwenhuijzen et al.
- Cyan line: Kudritzki et al., van Loon et al.
- Magenta line: Vink et al., van Loon et al.

- Black line: $\eta = 1.0$
- Dotted black line: $\eta = 0.33$
- Dashed black line: $\eta = 0.1$
$M(t)$ for $M_{\text{ZAMS}} = 15M_\odot$ with MESA

Only $\eta = 1.0$

- Vink et al., de Jager et al.
- Kudritzki et al., Nieuwenhuijzen et al.
- Kudritzki et al., de Jager et al.
- Vink et al., Nieuwenhuijzen et al.
- Kudritzki et al., van Loon et al.
- Vink et al., van Loon et al.
- $\eta = 1.0$
- $\eta = 0.33$
- $\eta = 0.1$
Comparison of Hot Wind Algorithms

Example: $M_{\text{ZAMS}} = 15M_\odot$ evolutionary tracks

$\Rightarrow$ Early (“hot”) wind influences subsequent evolution
Why Blue Loops? 1/2

- Blue loop ⇔ Large He-core
- Convection mixes H down, determining $M_{\text{He}}$
- $\mu$ is higher in He-rich regions

![Graph showing relation between mass and density for different $\eta$ values.]

- $M_{\odot}$, Vink et al., $T_{\text{eff}} = 15000$ K
- $\eta = 1.0$
- $\eta = 0.1$
- $\eta = 0.33$

- $M_{\odot}$, Kudritzki et al., $T_{\text{eff}} = 15000$ K
- $\eta = 1.0$
- $\eta = 0.1$
- $\eta = 0.33$
Why Blue Loops? 2/2

- Blue loop starts when H-burning shell reaches the edge of the He core
- Lower $\mu$ and higher $X \Rightarrow$ Variations of $\varepsilon_{\text{nuc}}$
- Envelope responds on its thermal timescale

\[ \downarrow \]

- if $\eta < 1 \Rightarrow$ He core edge too deep for Blue Loops
- Vink et al. rate yields larger cores allowing for Blue Loops
Why **not** Blue Loops?

Density profiles at the onset of Blue Loops

- Hot wind: Vink *et al.*, $\eta = 1.0$
- $M_{\text{ZAMS}} = 15M_\odot$
- Age $\approx 13.3$ [Myr]
- $\epsilon_{\text{nuc}} \geq 10^4$ [erg g$^{-1}$ s$^{-1}$]
Why not Blue Loops?

Density profiles at the onset of Blue Loops

$\log_{10}(\rho \text{ [g cm}^{-1}])$

$\varepsilon_{\text{nuc}} \geq 10^4 \text{ [erg g}^{-1} \text{ s}^{-1}]$

Ideal gas EOS: $P_{\text{gas}} = \frac{\rho}{\mu m_p} k_b T$

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

age $\approx 13.3$ [Myr]

$\varepsilon_{\text{nuc}} \geq 10^4$ [erg g$^{-1}$ s$^{-1}$]

Hot wind: Vink et al., $\eta = 1.0$
Summary

Results of the Comparison of Wind Algorithms:

- $\eta$ has a larger influence on the final mass than the wind algorithm;
- Early ("hot phase") mass loss influences the further evolution;
- $\dot{M}$ is more uncertain when it is higher (RSG phase);
- Different algorithmic representations of stellar winds $\Rightarrow$ Qualitatively different evolutionary tracks;
- Small number (8) of WR stars, none with $\eta < 1$ $\Rightarrow$ Other mass loss mechanism(s) to form WR?
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Why Impulsive Mass Loss?

Observational Evidence:
- LBVs
- Progenitors of H-poor core collapse SNe ($\sim 30\%$)
- Dense CSM for Type IIn SNe

Theory: Dynamical Events $\Rightarrow$ MESA not ready
- Pulsational Instabilities
- Roche Lobe Overflow in binaries
- Catastrophic Eruption(s)

$$\Delta M_{\text{wind}} \ll \Delta M_{\text{impulsive}} (\,?)$$
Remove mass in steps of $1M_\odot$, \( \max\{\Delta M_{\text{impulsive}}\} = 7M_\odot \).

Red dot: \( T_{\text{eff}} = 10^4 \text{ [K]} \); Yellow Triangle: \( R \geq R_{\text{max}}/2 = 375R_\odot \); Cyan Diamond: Maximum Extent Convective Envelope.
Chosen Stripping Points

$M = 15M_\odot$, $Z = Z_\odot$

\[ t(\text{MCE}) - t(\text{mSGB}) \simeq 10^4 \text{ [yr]} \ll 14.13 \times 10^6 \text{ [yr]} \]
Evolutionary tracks depend only on $\Delta M_{\text{impulsive}}$. 

![HR diagram with evolutionary tracks](image)
Evolution toward Higher $T_{\text{eff}}$

Impulsive + wind mass loss drives blueward evolution
pre-SN Stripped Structures

![Graph showing pre-SN stripped structures with log10(ρ/[g cm^{-3}]) vs. M [M⊙]. The graph includes plots for unstripped, mSGB 1M⊙, mSGB 2M⊙, mSGB 3M⊙, MCE 1M⊙, MCE 2M⊙, MCE 3M⊙, hMR 1M⊙, hMR 2M⊙, hMR 3M⊙, hMR 5M⊙, hMR 7M⊙, and MCE 5M⊙. The graph highlights different core compositions and mass ranges.]
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Conclusions

- Large systematic uncertainties in massive star mass loss rates
- Different algorithms $\Rightarrow$ Qualitatively different evolutionary tracks
- Uncertainty increases at higher $M_{ZAMS}$ and $\eta$

- Combined impulsive + wind mass loss drives blueward evolution
- Does impulsive mass loss have an effect on the “Explodability” of the star?

Thank you for your attention.
Figure Credits

Roughly in order of appearance.
Some figure were modified.
Figure not listed are from myself.
Click for original link.

- 30 Doradus (Tarantula Nebula)
- Observative HR
- Crab Nebula
- Orion
- Reionization Epoch
- Bubble Nebula
- SN1987A
- CCSN entropy rendering
- SN observations
- $\eta$ Car
- Betelgeuse

- Mass Loss Rate plot
- AG car
- Type Ib SN
- WR 124
- WR spectra
- P Cygni (34 Cyg)
Roche Lobe OverFlow

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

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

\[ \kappa \text{ [cm}^2\text{g}^{-1}] \]

\[ \text{OPAL: } X = 0.7, \log(\rho/T_6^3) = -5 \]

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

**MLT++:**

\[ \nabla T - \nabla_{\text{ad}} \rightarrow \alpha \nabla f \nabla (\nabla T - \nabla_{\text{ad}}) \]

\[ \alpha \nabla \equiv \alpha (\beta, \Gamma_{\text{Edd}}), \quad f \nabla \ll 1 \]

Figure: From Paxton et al. 2013, ApJS, 208, 5p
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: \( v(r) \approx \left( 1 - \frac{r}{R_*} \right)^\beta \) with \( \beta \approx 1 \)
- Chemical composition and ionization fraction
- Spherical symmetry: \( \dot{M} = 4\pi r^2 \rho v(r) \)
- 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 (≠ 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

\[ \log_{10}(T_{\text{eff}}/[K]) \]

\[ \log_{10}(L/L_\odot) \]

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

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

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

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

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

\text{Vink et al., de Jager et al.}
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Vink et al., de Jager et al.
Evolution of a Massive Star in one Slide

Vink et al., de Jager et al.

$\log_{10}(T_{\text{eff}}/[K])$

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$M = 15 M_{\odot}$, $Z = Z_{\odot}$

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

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

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

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

OC

SGB

RSG

H rich

He rich

C rich

O rich

Si rich

Fe rich

$Z = Z_{\odot}$
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.
Figure: Morozova et al. – arXiv:1505.06746
$R(t)$ for $15M_\odot$ Models during Blue Loops
End of the hot evolutionary phase

Vink et al. only: $T_{\text{jump}} \sim 25 \text{ [kK]} \Rightarrow \text{Fe}^{3+} \rightarrow \text{Fe}^{2+}$

$M_{ZAMS} = 25M_{\odot}$

$M_{ZAMS} = 30M_{\odot}$

$M_{ZAMS} = 20M_{\odot}$

$M_{ZAMS} = 15M_{\odot}$
Stellar counts

- Cannot be compared to clusters or single populations
- Higher $\eta \Rightarrow$ lower $M \Rightarrow$ slower evolution
- Different cut-offs in $L$ and $T_{\text{eff}}$
- Kudritzki et al. rate with $\eta = 1.0$ produces a loop in the HR diagram tracks, resulting in the over-population shown.
$M(t)$ for $M_{\text{ZAMS}} = 20 M_\odot$ with MESA
The graph shows the mass evolution $M(t)$ for $M_{ZAMS} = 25M_\odot$ with the MESA code. Various authors (Vink et al., de Jager et al., Kudritzki et al., Nieuwenhuijzen et al., etc.) have contributed to the study, and different efficiency parameters $\eta$ are considered: $\eta = 1.0$, $\eta = 0.33$, and $\eta = 0.1$. The mass at the terminal age main sequence (TAMS) is marked by a vertical line. The mass $M$ is expressed in units of solar masses $M_\odot$, and time $t$ is given in Myr.
$M(t)$ for $M_{ZAMS} = 30M_\odot$ with MESA

- Vink et al., de Jager et al.
- Kudritzki et al., de Jager et al., Hamman et al.
- Kudritzki et al., Nieuwenhuijzen et al.
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- $\eta = 1.0$
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$t$ [Myr]