The WN population in the Magellanic Clouds

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Resolved And unresolved Stellar PopUlaTIoNs (RASPUTIN) – Garching 2014
Wolf Rayet Stars (WR)

- evolved massive stars
  → initial masses above $20M_\odot$
- OB → (BSG/LBV) → WR
- dense and fast stellar winds
  (up to $\approx 5000 \text{ km/s}$)
- strong mass loss ($10^{-5}M_\odot/\text{yr}$)
- spectra with strong broad emission lines
  - helium and nitrogen
    → WN sequence
  - carbon, helium, and oxygen
    → WC sequence
PoWR: Potsdam Wolf-Rayet model code for expanding stellar atmospheres with spherical stellar winds

Features:
• full Non-LTE calculation of population numbers
• complex model atoms (H, He, N, C, O, ...)
• radiative transfer in co-moving frame
• pressure broadening in formal integral
• iron-line blanketing (super-level approach)
• wind inhomogeneities (micro-clumping)
• applicable to hot stars (WR, O, B, LBV, CSPN ...)

PoWR models: www.astro.physik.uni-potsdam.de/PoWR.html
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Spectral analysis

**Aim:** reproduce the complete spectra instead of individual lines

**Results:**
- obtain consistent set of stellar parameters
  \[ T_*, L, \dot{M}, v_\infty, \ldots \]
**Magellanic Cloud sample**

**Large Magellanic Cloud**
- nearly complete WN population (101 of 117 WN stars) → Hainich et al. (2014)
- 31 binaries/binary suspects (Foellmi et al. 2003b)

**Small Magellanic Cloud**
- complete WN population
- 7 single stars + 4 binaries (Foellmi et al. 2003a)
- single: Hainich et al. (in prep.)
- binary: Shenar et al. (in prep.)
WN spectra: comparison between LMC and SMC

**WN stars:** helium & nitrogen emission lines

- **WN E:** WN 2 - WN 5
- **WN L:** WN 6 - WN 11

**SMC:**
- considerably weaker emission lines
- inherent absorption lines
- photosphere might be partly visible
- weaker winds → metallicity effect
**WN spectra: comparison between LMC and SMC**

**WN stars:** helium & nitrogen emission lines

**LMC**

**SMC:**
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\[ \dot{M} - Z \text{-relation} \]

- **\dot{M} - Z relation:**
  - Averaged \( \dot{M} \) for each galaxy
  - \( Z_{MW} = 0.014 \)
  - \( Z_{LMC} = 0.006 \)
  - \( Z_{SMC} = 0.002 \)

\[ \log \left( \frac{\dot{M}}{(M_{\odot} \text{ yr}^{-1})} \right) \]

\[ \log (Z) \]

\[ -2.8 \quad -2.6 \quad -2.4 \quad -2.2 \quad -2.0 \quad -1.8 \quad -1.6 \]
$\dot{M}$--$Z$-relation

$\dot{M} \propto Z^{0.9}$

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weighted fit:

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\( \dot{M}-Z \)-relation

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**Mass-loss prescription for WN stars:**
(\( \chi^2 \)-fit to the whole dataset)
**\( \dot{M} - Z \)-relation**

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**weighted fit:**

\[
\dot{M} \propto Z^{0.9}
\]

**Mass-loss prescription for WN stars:**

(\( \chi^2 \)-fit to the whole dataset)

\[
\dot{M} = -12.6 + 2 \log(1 + X_H) + 2.3 \log(L/L_\odot) - 2.5 \log(M/M_\odot) + 0.7 \log(Z)
\]
Evolutionary status of the WN stars
Stellar evolution: LMC


- $Z = 0.008$
- with rotation
- $M_{WR, ini} \approx 30 M_\odot$, deduced initial WR mass: $\approx 20 M_\odot$

R. Hainich et al. WN population in the MCs
Stellar evolution: LMC

- $Z = 0.008$
- with rotation
- $M_{\text{WR,ini}} \approx 30 \, M_{\odot}$
Stellar evolution: LMC

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deduced initial WR mass:
- $\approx 20 \, M_\odot$
SMC WN stars: comparison with LMC and MW sample

MW sample:
- Hamann et al. (2006)
- Martins et al. (2008)
- Liermann et al. (2010)
- Oskinova et al. (2013)

LMC sample:
- Hainich et al. (2014)

SMC sample:
- considerably more luminous
SMC WN stars: comparison with LMC and MW sample

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LMC sample:
- Hainich et al. (2014)

SMC sample:
- considerably more luminous
- all with hydrogen

Graph showing the comparison of luminosity and temperature between SMC, LMC, and Galactic WN stars with different hydrogen percentages: 
- SMC: WNL < 30% H, ≥ 30% H
- LMC: WNL, WNE
- Galactic: WNL, WNE

The graph also shows the positions of stars with and without hydrogen, with He-ZAMS and ZAMS markers.
Stellar evolution: SMC

Evolution tracks from Eldridge & Vink (2006)
- $Z = 0.004$
- without rotation
- $M_{\text{WR,ini}} \approx 45 \, M_{\odot}$

deduced initial WR mass: 
\[ \approx 30 - 35 \, M_{\odot} \]
Stellar evolution: SMC

Evolution tracks from Eldridge & Vink (2006)

- $Z = 0.004$
- without rotation
- $M_{WR,ini} \approx 45 \, M_\odot$

deduced initial WR mass:

$\approx 30 - 35 \, M_\odot$
Stellar evolution: SMC

Geneva evolution tracks: Georgy et al. (2013)
- $Z = 0.002$
- with rotation
- $M_{\text{WR,ini}} \approx 85 M_\odot$

Deduced initial WR mass:
\[ \approx 30 - 35 M_\odot \]
Stellar evolution: SMC – quasi homogeneous evolution

Homogeneous evolution:
- proposed by Martins et al. (2005)

Evolution tracks from Brott et al. (2011)
- $Z = 0.002$
- $v_{\text{rot,ini}} \approx 500 \text{ km/s}$

- fail to reproduce the observed surface abundances
Conclusions

Open question:
How to explain the observed hydrogen abundance for SMC WN stars simultaneously with their individual HRD positions?

Stellar evolution models:
- still partly fail to reproduce the observed WN parameter range
  - predicted initial WR mass to high
  - SMC: observed hydrogen abundances cannot be reproduced

Stellar wind mass loss:
- winds of SMC WN stars weaker than their MW and LMC counterparts
- mass-loss prescription for WN stars:
  \[ \dot{M} = -12.6 + 2 \log(1 + X_H) + 2.3 \log(L/L_\odot) - 2.5 \log(M/M_\odot) + 0.7 \log(Z) \]
Stellar evolution: SMC – old generation of Geneva models

Geneva evolution tracks:
Meynet & Maeder (2005)
- \( Z = 0.004 \)
- with rotation
- \( M_{\text{WR,ini}} \approx 40 M_\odot \)

deduced initial WR mass:
\( \approx 30 – 35 M_\odot \)
Binary evolution

Radial velocity study:
Foellmi et al. (2003a)

Binary evolution:
Evolution tracks from Eldridge et al. (2013)
- $Z = 0.02$
- evolution tracks for the primary
- also fail to reproduce the observed surface abundances
Binary evolution

Radial velocity study:
Foellmi et al. (2003a)

Binary evolution:
Evolution tracks from Eldridge et al. (2013)

- $Z = 0.02$
- evolution tracks for the primary

also fail to reproduce the observed surface abundances
Bat117

DM = 18.5 mag  $E_{b-v} = 0.19$

$M_v = -6.33$ mag  $v_{rad} = 250$ km/s

$E_{b-v} = 0.19$

$v_{rad} = 250$ km/s

$M_v = -6.33$ mag

log $f\lambda$ [erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$]

log $\lambda$ [Å]

Relative flux

$\lambda$ [Å]

$\log f\lambda$ [erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$]

Relative flux

$\lambda$ [Å]
Radius problem of WR stars

- Observed $T_*$ of H-free WR stars much lower than predicted

Stellar envelope inflation

- Extended sub-photospheric layers
- Taking the effect of clumping into account (Gräfener et al. 2012)
- Solving the temperature discrepancy

![HRD of the Galactic WN stars](chart.png)

Credit: Gräfener et al. (2012)
Stellar evolution models vs. observation:

- hydrogen abundances are lower than observed
- in general the agreement seems to be better at higher metallicities
  - initial metallicity of SMC WN stars higher than $Z = 0.002$
    - $\rightarrow$ Piatti (2011): strongly age dependent $Z_{SMC}$
  - mass-loss rates higher than prescribed in stellar evolution models
  - missing physical ingredient
Line-driven stellar winds

(Castor, Abbott & Klein 1975, "CAK")

- absorption mainly from radial directions but isotropic re-emission ⇒ acceleration ⇒ velocity ↑ ⇒ Doppler shift of the line
- photons from whole frequency band $\Delta \nu$ are swept up
- intercepted momentum per time and line: $L_{\nu_0} \Delta \nu / c = L_{v_\infty} / c^2 = \dot{M}v_\infty$
- mass loss by each thick line: $\dot{M} = L / c^2 \equiv \dot{M}$ by nuclear burning
- fails for WR stars ↔ WR mass loss exceeds the single scattering limit

\[ L \approx L_{\nu_0} \nu_0 \]
Modified wind momentum-luminosity relation

\[ D_{\text{mom}} - L\text{-relation:} \]

compared to the results for LMC OB stars (Vink et al. 2000, 2001; Mokiem et al. 2007)

- Wind momentum:
  \[ D_{\text{mom}} = \dot{M} v_\infty R_*^{1/2} \]

winds of SMC WR stars
\[ \approx \]
winds of O stars