Effects of low metallicity on the evolution and spectra of massive stars

Jose Groh (Geneva Observatory, Switzerland)
Take Away: effects of low metalliclicity

- Reduced stellar wind mass and angular momentum losses
- Stars are more compact, hotter, and more mixed
- Spectral lines are weaker and less numerous; more ionizing flux
Outline

- Background on massive stars and stellar evolution
- Effects of low metallicity on stellar evolution
- Effects of low metallicity on stellar spectra
- Scary things
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- Background on massive stars and stellar evolution
  - Effects of low metallicity on stellar evolution
  - Effects of low metallicity on stellar spectra
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Massive stars bridge many fields of (astro)Physics

- Star formation
- Photoionized regions, chemical evolution
- Supernova, GRBs, Black Holes, Neutron Stars
- Distant Universe (starbursts, first stars, cosmology)
- Intergalactic, interstellar, circumstellar media
- High-energy physics, particle physics, ...
- Stellar evolution
Massive star evolution is challenging.

Diagram:
- Luminosity axis labeled vertically.
- Effective Temperature axis labeled horizontally.
- OB-type at ZAMS indicated on the diagram.
Massive star evolution is challenging.
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Massive star evolution is challenging

Science we want to do
- Evolutionary channels
- Initial mass ranges
- SN type + progenitor
- Single x binary evol.
- Metallicity effects, ...

Effective Temperature

Luminosity

Wolf-Rayet

Luminous Blue Variable

Yellow Hyper-Giant

Red Super-Giant

OB-type at ZAMS
Massive star evolution is challenging

Science we want to do
- Evolutionary channels
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However
- Rarity of massive stars
- Mass loss + rotation
- Binarity
- Models vs. observations
Five flavors
Single stellar evolution models

Five flavors

- non-rotating Eldridge talk
Single stellar evolution models

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- differential rotation (NO MAGNETIC FIELDS)
Single stellar evolution models

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  Leitherer talk; Levesque talk

binaries: de Mink talk
Single stellar evolution models

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- differential rotation (NO MAGNETIC FIELDS)
  - Leitherer talk; Levesque talk
- solid-body rotation (WITH MAGNETIC FIELDS) Yoon talk

Five flavors

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Single stellar evolution models

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- solid-body rotation (WITH MAGNETIC FIELDS)
  - Yoon talk
- differential rotation with surface magnetic braking
Single stellar evolution models

Five flavors

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Observational constraints are key

- asteroseismology: differential x solid-body rotation
- spectroscopy+polarimetry: rotation and magnetic fields
- Metallicity dependence?
Rotating massive star evolution models at solar metallicity

Z=0.014

(Groh+ 13b after Ekstrom+12, Georgy+ 12)
Rotating massive star evolution models at solar metallicity

\[ Z = 0.014 \]

~8 to 17 \( M_\odot \)

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Rotating massive star evolution models at solar metallicity

Z = 0.014

~8 to 17 $M_\odot$

~17 to 30 $M_\odot$

OB-type $\rightarrow$ RSG $\rightarrow$ SN II P

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Rotating massive star evolution models at solar metallicity

\[ Z = 0.014 \]

~8 to 17 \( M_\odot \)

OB-type \( \rightarrow \) RSG \( \rightarrow \) YHG/LBV \( \rightarrow \) SN IIL/b

OB-type \( \rightarrow \) RSG \( \rightarrow \) SN IIP

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Rotating massive star evolution models at solar metallicity

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$> ~30 \ M_\odot$

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\begin{itemize}
  \item \( \sim 8 \) to \( 17 \) \( M_\odot \)
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\end{itemize}

\begin{itemize}
  \item OB-type
  \item LBV
  \item WR
  \item SN Ibc
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A change of metallicity affects:

1. Opacities
2. Equation of state (via mean molecular weight)
3. Nuclear reaction rates
4. Fuel available during MS \((X = 1 - Y - Z)\)
5. Mass and angular momentum losses from stellar winds
6. Rotational effects and angular momentum transport
Rotating massive star evolution models at SMC metallicity

Z = 0.002 (i.e. 1/7 Z\text{sun})

>50 M\text{\(\odot\)}

8 to 50 M\text{\(\odot\)}

(Groh+ 15 in prep after tracks from Georgy+ 13)
Rotating massive star evolution models at SMC metallicity

Z=0.002 (i.e. 1/7 Zsun)

OB-type → RSG → SN IIP

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Rotating massive star evolution models at SMC metallicity

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Rotating massive star evolution models at ~ IZw18 metallicity

Z=0.0004 (i.e. 1/50 Zsun)

(Groh+ 2015 in prep)
Rotating massive star evolution models at ~ I Zw18 metallicity

Z = 0.0004 (i.e. 1/50 Zsun)

O B-type RSG/BSG SN IIP

M⊙

(Groh+ 2015 in prep)
Rotating massive star evolution models at ~ Izw18 metallicity

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OB-type → YHG/LBV → SN IIP or IIn

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Z=0.0004, rot.

(Groh+ 2015 in prep)
Rotating massive star evolution models at ~ I Zw 18 metallicity

Z = 0.0004 (i.e. 1/50 Z\textsubscript{sun})

<table>
<thead>
<tr>
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Stars reach the RSG phase only at late times: less RSGs
Metallicity trends in stellar evolution
Low metallicity: mass loss diminishes

Groh+ 2015, in prep
Low metallicity: stars are more compact and hotter

Groh+ 2015, in prep
Low metallicity: faster surface rotation

For high mass stars:
Reduced mass and angular momentum losses from stellar winds
Low metallicity: chemical mixing is favored

At low Z: stars are more compact; transport of angular momentum is less efficient.

Relative Nitrogen enhancement

blue= initial angular velocity $\Omega/\Omega_{\text{crit}} = 0.10$
purple= initial angular velocity $\Omega/\Omega_{\text{crit}} = 0.95$
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How to compare observations and stellar evolution models?

Issue: massive stars develop winds that become denser as the star evolves, hiding progressively more and more of the stellar surface.
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low-mass stars
(e.g. Sun)
How to compare observations and stellar evolution models?

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Observations: $r_{\text{hydr}} = r_{\text{phot}}$

low-mass stars (e.g. Sun)

massive stars: low $\dot{M}$

Evol. code

Observations
Issue: massive stars develop winds that become denser as the star evolves, hiding progressively more and more of the stellar surface.

Consequence: challenging to compare interior models of massive stars and observations.
Solution: merge with an atmospheric code

Mass
Luminosity
Temperature
Surface abundances

Magnitudes
Colors
SED
Spectrum
Unified stellar evolution and atmospheric modelling

non-rotating 60 M\(_\odot\) at solar Z

Spectral evolution of a non-rotating 60 Msun star

Spectral evolution of a non-rotating 60 Msun star

Unified stellar evolution and atmospheric modeling

See also Schaerer+96, Schaerer & de Koter 96

Groh+ 2014
merge T and density structures from stellar evolution and atmospheric codes

+ post-processing on a large grid of models
+ flexibility to study the effects of mass loss
+ effects of line blanketing, wind clumping
Unified stellar evolution and atmospheric modeling

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(Groh+ 14)
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Error of computing spectra assuming Teff(stellar evolution):
200-500K (ZAMS)
1500-4000 K (O supergiants)
10000s K (WR stars and LBVs)

(Groh+ 14)
Metallicity effects on stellar spectra: unified models

mid-H burning non-rotating $60 M_\odot$ at $Z=0.014$ (O4 I; $\text{Teff}=43kK$)

(Groh+ 15 in prep)
Metallicity effects on stellar spectra: unified models

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(Groh+ 15 in prep)
Metallicity effects on stellar spectra: unified models

He II 4686 line is weaker at low Z = Mdot effect (20x lower)
Spectral lines are less numerous (CNO) = abundance effect (50x lower)

(mid-H burning non-rotating 60 M\(_{\odot}\) at Z=0.014 (O4 I; Teff=43kK)
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Normalized Flux

Wavelength [Angstrom]
Metallicity effects on stellar spectra: unified models

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Metallicity effects on stellar spectra: ionizing fluxes

mid-H burning non-rotating 60 M_☉ at Z=0.014 (O4 I; Teff= 43kK)

Flux (erg/s/cm^2/Angstrom)

Wavelength [Angstrom]

(Groh+ 15 in prep)
Metallicity effects on stellar spectra: ionizing fluxes

increase in ionizing fluxes (abundance/line blanketing effect)

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mid-H burning non-rotating 60 $M_\odot$ at $Z=0.014$ (O4 I; $T_{\text{eff}}=43kK$)

(Flux in erg/s/cm$^2$/Angstrom)
Scary things: how do they change with metallicity?

- Mass loss and eruptions
- Wind structure (clumping)
- Blackbody vs model atmosphere
- Binarity
- Magnetic Fields
- Rotation
- Convection
- Eddington limit and inflation
Scary things: how do they change with metallicity?

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Wind clumping affects line profiles

MPG 355 (O2 III) in NGC 346

(Teff=52kK Z=0.002 Mdot 2.5e-6 Msun/yr)

(Bouret et al. 2003)
Wind clumping affects line profiles

MPG 368 (O4-5 V) in NGC 346

atmospheric models with clumping not included in Stellar Pop. Synthesis

(Te$	ext{ff}=40kK$ Z=0.002 M$	ext{dot}$ 1e-7 Msun/yr) (Bouret et al. 2003)
Clumping and Mdot effects?

(courtesy C. Steidel)
Blackbody vs. Model atmospheres
(or why I don’t like blackbodies)

Black = CMFGEN model, Teff = 47kK, Z = 0.0004
Red = Blackbody T = 47kK
Red = Blackbody T = 60kK
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