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   • Some present-day challenges in the physics of RSGs
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3 RSG as a population
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Introduction

To be or not to be a RSG
RSG as a population

Why are RSGs interesting objects?
Some present-day challenges in the physics of RSGs
Some crucial questions for the evolutionists
Why are RSGs interesting objects?

if all stars with $M \approx 8 - 25 M_\odot$ go through a RSG phase:

80% of all massive stars will be a RSG one day!

crucial phase for mass loss

progenitors of type II cc-SNe
Why are RSGs interesting objects?

### Evolutionary Scheme: The (Modified) Conti Scenario (Conti, 1975)

<table>
<thead>
<tr>
<th>Mass Range</th>
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<th>Supernova Type</th>
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<tbody>
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Why are RSGs interesting objects?

**evolutionary scheme: the (modified) Conti scenario** *(Conti, 1975)*

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Evolutionary scheme: the (modified) Conti scenario

\[ M > 60 M_{\odot}: \quad O \rightarrow \text{Of/WNL} \rightarrow \text{LBV} \rightarrow \text{WNL} \rightarrow \text{WC} \rightarrow \text{WO} \rightarrow \text{SNIbc} \]

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Real filiation depends on:

- Mass loss
- Overshooting
- Rotation
- Magnetic fields
- Interactions in close binaries
Why are RSGs interesting objects?

easily seen in external galaxies

Neugent et al. (2012)

Lançon et al. (2009)

Drouet et al. (2012)
Why are RSGs interesting objects?

they can be used as indicators:

**metallicity indicators**

*(Davies et al., 2010; Bergemann et al., 2012)*

see Rolf Kudritzki’s talk

when only modest resolution \((R = 2 - 3000)\) is available

\(Z\) determination is robust

for \(T_{\text{eff}}\): needs higher \(R\)
Why are RSGs interesting objects?

they can be used as indicators:

- **distance indicators**
  (cf. Rolf Kudritzki’s or Ben Davies’ talks?)

- **age indicators**
  (Lançon et al., 2009)

RSG phase limited in mass range and to advanced stage of stellar evolution

- **important sources of dust in the Universe**
Some present-day challenges in the physics of RSGs

- physics of convection
  - non adiabatic
  - supersonic turbulence

- mass loss
  - rates?
  - steady or bursts?

\[ R_{\text{core}} \approx 0.5 R_\odot \]
\[ R_{\text{env}} \approx 800 R_\odot \]
Some crucial questions for the evolutionists

- when does a massive star enter into the RSG phase?
- how long does this phase last?
- what is the impact of the available physics?
- what types of cc-SNe arise from RSGs?
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  - convection?
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  - rotation, magnetic fields?
  - multiplicity?
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- When does a massive star enter into the RSG phase?
- How long does this phase last?
- What is the impact of the available physics?
  - Convection?
  - Mass loss?
  - Rotation, magnetic fields?
  - Multiplicity?
- What types of cc-SNe arise from RSGs?
  - Type II-P, II-L?
  - No SN event if black hole?
To be or not to be a RSG

RSGs evolution

S. Ekström

26.11.12
When do massive stars enter into the RSG phase?

New grids of stellar models:

- updated abundances \textit{(Asplund et al., 2005)}, opacities, and reaction rates
- rotation prescriptions from \textit{Maeder (1997) and Zahn (1992)}
- improved treatment of rotation with angular momentum conservation
- mass loss
  - \textit{Vink et al. (2001)} for O-stars
  - \textit{de Jager et al. (1988)} for RSGs
  - $\dot{M} \times 3$ if supra-Eddington layers ($M \geq 20 M_\odot$)
  - $\dot{M}$ close from \textit{van Loon et al. (2005)} rates
When do massive stars enter into the RSG phase?

**mass range:**
9 – 40 $M_\odot$

**age range:**
$4.5 \cdot 10^6 – 30 \cdot 10^6$
When do massive stars enter into the RSG phase?

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When do massive stars enter into the RSG phase?

mass range: $9 - 25 \, M_\odot$

age range: $8 \cdot 10^6 - 35 \cdot 10^6$

high mass: rotation mixing keeps the star in the blue
When do massive stars enter into the RSG phase?

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high mass: rotation mixing keeps the star in the blue
When do massive stars enter into the RSG phase?

rotating 15 models at $Z_\odot$, Georgy et al. (submitted)

- a little rotation favours the crossing to the red
- too much rotation keeps the star in the blue

In real stellar populations: velocity distribution
When do massive stars enter into the RSG phase?

(rotating 15 $M_\odot$ models at $Z_{\text{SMC}}$, Meynet et al. (2012))

dependent on the prescription used for rotation
When do massive stars enter into the RSG phase?

dependent on the prescription used for rotation

Global trend:

A large core with a H-b shell associated to a narrow conv. z. favours the redward crossing
When do massive stars enter into the RSG phase?

**effect of metallicity:**
- He-b mostly in the blue
- late HRD crossing

**short duration of RSG phase!**

\[Z_\odot: \text{RSGs are He-b stars} \]
\[\text{low } Z: \text{C-b stars} \]

*cf. Jose Groh’s poster*
When do massive stars enter into the RSG phase?

- effect of metallicity:
  - He-b mostly in the blue
  - late HRD crossing

- short duration of RSG phase!

- $Z_{\odot}$: RSGs are He-b stars
- low $Z$: C-b stars

*cf. Jose Groh's poster*
How long does the RSG phase last?

the higher the mass loss, the shorter the RSG phase
cf. Cyril Georgy’s talk

transition around $18 - 20 \, M_\odot$

in the models:
due to the treatment of supra-Eddington layers for $M \geq 20 \, M_\odot$
How long does the RSG phase last?

BUT:

- sensitivity to supersonic convection around 20 $M_\odot$

- cf. *Smartt (2009)*: no RSG progenitors for SN II-P above 18 $M_\odot$

note that most of the RSG observed (80%) would come from the low mass-loss group
Can we distinguish a former rapid-rotator?

- Radius inflation: $V_{eq}$ decreases strongly.
- Impact of the time spent in the crossing.
- Higher initial rotation rate: slow crossing.
- Angular momentum loss through winds.

15 $M_{\odot}$ models at $Z_{\odot}$ from Georgy et al. (2012, submitted)

Impact of the time spent in the crossing:
- Higher initial rotation rate: slow crossing.
- Angular momentum loss through winds.
Can we distinguish a former rapid-rotator?

- high initial rotation rate:
- slow, but not so slow!
- surface enrichment by a factor of 50-60 for the former most rapid-rotators
RSG as a population
the mass lost in the RSG phase is enriched with He and secondary N

is it significant for the chemical evolution of galaxies?

probably no:
for those elements, most contributors will be intermediate-mass stars

they are important dust producers in the Universe
Universe enrichment through mass loss

non-rotating models at $Z_\odot$ from Hirschi et al. (2004)

\begin{align*}
\nu_{\text{ini}} &= 0 \text{ km s}^{-1} \\

\text{Stellar yields / initial mass} &\quad \text{Initial Mass [M}_\odot]\end{align*}
with rotation: for $M < M_{WR}$, $^{12}$C and $^{16}$O increased by a factor of 2
yields of a 30 $M_{\odot}$ at 20 $M_{\odot}$
RSGs in clusters

**COEVAL**

Population ratios can be predicted by:

Ratio of IMF integrated over the initial mass range responsible for the type of star considered.

→ Constraints on mass limits

**CONSTANT STAR FORMATION**

Population ratios can be predicted by:

Ratio of IMF, weighted by the duration of the phase, integrated over the initial mass range responsible for the type of star considered.

→ Constraints on mass limits and durations
RSGs in coeval clusters: the RSG to MS stars ratio

MS stars: 2 mag below TO
R(S)Gs: $T_{\text{eff}} \leq 3.70$

Peak of the ratio when high-$L$ RSGs dominate

valley in the age range of large-loop Cepheids

increase again at red giants time
MS stars: 2 mag below TO
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Peak of the ratio when high-$L$ RSGs dominate

valley in the age range of large-loop Cepheids

increase again at red giants time

stochastic effect in small clusters
RSG and WR populations

In single star scenario:

almost no overlap between WRs and RSGs populations

test for the binarity channel of WR?

(rotating models from Ekström et al. (2012))
Note on SNe progenitors

Maund & Smartt (2005), Maund et al. (2005): lack of high-$L$ progenitors for type Ibc SNe

interpreted as an indication of low-mass progenitors in binaries

however, Yoon et al. (2012) show large BC for massive WR stars
Note on SNe progenitors

**Groh et al. (submitted to A&A letters)**

Coupling the Geneva stellar evolution models with the CMFGEN atmosphere code:

**LBVs as direct SNe progenitors**
Introduction

To be or not to be a RSG

RSGs as a population

Universe enrichment

RSGs in coeval clusters

RSGs in constant star formation regions

RSGs in constant star formation regions: the RSG to WR ratio

Massey (2002)

at $Z_{\odot}$: $N_{\text{RSG}}/N_{\text{WR}} = 0.2$

strong metallicity trend: $Z \downarrow \rightarrow N_{\text{RSG}}/N_{\text{WR}} \uparrow$
RSGs in constant star formation regions: the RSG to WR ratio

at \( Z_{\odot} \): \( N_{\text{RSG}}/N_{\text{WR}} = 0.2 \)

strong metallicity trend: \( Z \downarrow \rightarrow N_{\text{RSG}}/N_{\text{WR}} \uparrow \)

non-rotating models: good \( Z \)-trend but too high

rotating models: ok at \( Z_{\odot} \), \( Z \)-trend not reproduced
The BSG to RSG ratio

at $Z_\odot$: $N_{\text{BSG}}/N_{\text{RSG}} \sim 3$

strong metallicity trend: $Z \downarrow \rightarrow N_{\text{RSG}}/N_{\text{WR}} \downarrow$
The BSG to RSG ratio

at $Z_\odot$: $N_{\text{BSG}}/N_{\text{RSG}} \sim 3$

strong metallicity trend: $Z \downarrow \rightarrow N_{\text{RSG}}/N_{\text{WR}} \downarrow$

models: ± ok at $Z_\odot$
much too high ratio at $Z_{\text{SMC}}$:
no rot: 94 - rot: 87

lack of RSGs at low $Z$
The BSG to RSG ratio

at $Z_{\odot}$: $N_{\text{BSG}}/N_{\text{RSG}} \sim 3$

strong metallicity trend: $Z \downarrow \rightarrow N_{\text{RSG}}/N_{\text{WR}} \downarrow$

models: ± ok at $Z_{\odot}$
much too high ratio at $Z_{\text{SMC}}$:
no rot: 94 - rot: 87

lack of RSGs at low $Z$

only the rotating 15 $M_{\odot}$: 65
with a velocity disturb.: 16
We have to conclude that massive star models in the considered mass range still lack some significant physical ingredient. However, we want to emphasize that this does not imply that the results of massive star theory have to be questioned altogether. The B/R-ratio is a quantity which is known to depend extremely sensitive on the model parameters. It is thus a welcome amplifier which can (and finally will) be very useful to constrain the model physics very accurately. Most other results of massive star calculations depend far less on the uncertain assumptions and can thus be used with much more confidence.

_Langer & Maeder (1995)_
Conclusion

- the mass loss in RSG phase is still not very well constrained steady? bursts? rates?

- the detailed physics leading to a RSG is not yet fully understood conditions to cross the HRD? loops?

- need for precise observations of RSGs characteristics $\dot{M}$ related to $L$, clusters with RSGs and WRs?
THANK YOU FOR YOUR ATTENTION!
References I


Conti, P. S. 1975, Memoires of the Societe Royale des Sciences de Liege, 9, 193 [ADS]


Maeder, A. 2009, Physics, Formation and Evolution of Rotating Stars (Berlin Heidelberg: Springer Verlag) [ADS]


References II


