THE EVOLUTION OF RED SUPERGIANTS TO supernova

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Outline

- Introduction to RSGs
- Evolution of RSGs to SN
- Mass-loss
- Age determinations
- Summary
RED SUPERGIANTS

- Evolved massive stars (8-25 M☉)
- Direct progenitors to Type II SN - powerful test of stellar evolutionary theory
EVOLUTION OF A 15M⊙ STAR

Core contracts... star swells up
Core contracts, star swells up.
Lots of convection in the envelope
EVOLUTION TO RSG PHASE

\[ \log(L/L_\odot) \]

\[ \log(T/K) \]

Credit: Ben Davies
THE PATH TO SUPERNOVA

- He-core gets exhausted, fuses into carbon core, which fuses into oxygen, which fuses into neon…
- Core gets heavier and heavier
- No more nuclear reactions
- Star collapses onto the core…

Core-collapse supernovae
What kind of SN depends on the appearance of the progenitor at core collapse
Strong winds peel away envelope
RSGs live $\sim 10^6$ yrs, mass-loss timescale ($M/M\text{dot}$) is about the same
Whole envelope can be peeled off through lifetime
TWO OPTIONS...

- ‘Wolf-Rayet’ (hot progenitor)
- Stripped/H-poor SN (type Ibc)

- RSG/YSG progenitor
- H-rich envelope intact
- Unstripped SN (Type II)
We know RSGs explode as II-P SNe
SN —> check archival images —> identify progenitor

Pre-explosion photometry + some assumptions allow us to find the terminal luminosity of the progenitor and infer a mass
Red supergiant problem...

Maximum IIP progenitor mass ~16M\textsubscript{sun}?

(a) STARS/ Geneva models

EVOLUTION FROM MS TO RSG

- Let us note that the dispersion of the initial rotational velocities towards the RSG phase (Stothers & Chin 1979; Maeder 1981).
- Very interestingly, for the 12 $M_\odot$ rotating model, the minimum mass coordinate reached by the outer convective zone is 6.6 $M_\odot$ while in the rotating model this is 2.6 $M_\odot$.
- As a consequence, in the rotating model during the first dredge-up, the outer convective zone proceeds much more deeply in mass than in the non-rotating star. Typically in the non-rotating model the minimum mass coordinate reached by the outer envelope is more extended, and is thus characterized by lower temperatures and higher opacities at a given mass coordinated.

**Figure 8.**

- Evolutionary tracks for non-rotating models with solar metallicity. The rotating massive stars are indicated by short-dashed lines. The long-dashed track for the 60 $M_\odot$ model corresponds to a very fast rotation (rotation period of 50 days).
- Let us end this section by saying a few words about the specific stars (M > 60 $M_\odot$), the present rotating models enter the red supergiant (RSG) phase already during the H-burning phase (see also Meynet & Maeder 1989), a blue loop appears when the gravitational potential of the core is inferior to a critical value $\Phi_{crit}$.
- The higher luminosity implies that the outer convective zone and therefore favours a rapid evolution towards the RSG phase. This results from the higher luminosity which produces a certain distribution of the above behaviours.

- In the rotating models with and without rotation, the models with rotation present very similar blue loops.
- The increase in luminosity is due mainly to the higher luminosities reached by the tracks computed through the formula proposed by Friend & Abbott 1986, which contributes to produce smaller final masses. For the most massive stars (M > 60 $M_\odot$), the present rotating models enter the RSG phase, dies a nearly homogeneous evolution. Only the low gravity objects present (if any) a mass discrepancy problem (see e.g. Herrero et al. 2000).
- For purpose of clarity, only the mass discrepancy between the evolutionary tracks and the mass estimates in some binaries (Penny et al. 1999) may explain some of the discrepancies between the evolutionary and the actual masses. This is especially true in the high mass star range in which the luminosity versus mass relation flattens. This is in the sense that fast rotators are overluminous with respect to their actual masses. This is especially true in the high mass star range in which the luminosity versus mass relation flattens (Langer 1992; Meynet 1998).
- A dispersion of the initial rotational velocities implies a dispersion of the luminosities at a given mass.
- The gravitational potential of the core and enables the apparition of a blue loop. Indeed the outer convective zone and therefore favours a rapid evolution towards the RSG phase. This explains the appearance of a blue loop in the HR diagram: for the non-rotating 15 and 20 $M_\odot$ models, respectively 25 and 20% of the total He-burning lifetime is spent at this stage. The behaviour of the rotating models is enhanced by 60–100% in rotating models with solar metallicity. The direct effect of rotation on the mass loss rates (in the present discussion in Maeder & Meynet 1989), a blue loop appears when rotation is included. This results from the higher luminosity which produces a certain distribution of the above behaviours.
what changed..?
- abundances, opacities, overshooting…
- **mass-loss rate implementation**
MASS-LOSS RATE IMPLEMENTATION

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

\begin{align*}
\text{in addition, in Ekstrom+ 2012:} \\
\text{if } L > 5L_{\text{Edd}}, \quad \dot{M} = \dot{M} \times 3 \\
(\text{kicks in at } \sim 20M_\odot)
\end{align*}

credit: Ben Davies
Mass-loss rates are not calculated from first principles.
EMPIRICAL MASS-LOSS RELATIONS

- Mass-loss rates are **not** calculated from first principles.
- Lots of internal scatter.

![Graph showing empirical mass-loss relations with data points and uncertainties.](image-url)
Mass loss rates in the Hertzsprung-Russell diagram

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Summary. — From the literature we collected values for the rate of mass loss for 271 stars, nearly all of population I, and of spectral types O through M. Rates of stellar mass loss determined according to six different methods were compared. The average mass loss rates for each method were calculated, and larger than the average are marked.

★ Highly heterogeneous sample (masses, metallicities…)

★ Highly heterogeneous methodologies (mid-IR excesses, abs line analysis, radio…)

★ No longer used for OBA

U : from ultraviolet spectra, mainly from far UV resonance line profiles;
V : from spectral lines in the visual and near ultraviolet spectral ranges, mainly subordinate lines such as \( \text{H}_\alpha \), but in some cases also from other lines, including the H and K lines;
I : from broad-band infrared photometric data, assuming the flux to be due to free-free emission;
C : from infrared data on C-molecular compounds;
M : from maser lines in the microwave range;
R : from radio continuum data: radiofluxes due to free-free emission, i.e. excluding data of stars for which the radio emission is assumed to be synchrotron radiation (cf. e.g. Underhill, 1984a).
By targeting RSGs in clusters, we can assume all RSGs are the same Z and same $M_{\text{ini}}$.

We can use $L$ as a proxy for evolution.
SOFIA - new data (PI N Smith)

WISE - archival

SPITZER - archival

MSX - archival
HOW DO WE MEASURE MASS-LOSS RATES?

- Dust layer absorbs and re-emits photons
- Mass-loss can be measured by modeling mid-IR excess
HOW DO WE MEASURE MASS-LOSS RATES?

The shape of this bump tells us about the dust composition, for RSGs it's silicate rich dust.

Light absorbed by dust here

Re-emitted here
We model this emission using a radiative transfer code (DUSTY), and derive a mass-loss rate for each RSG in the cluster.
Tight correlation…

Fixed initial mass and Z

Beasor & Davies 2016
HOW DO MASS-LOSS RATES CHANGE WITH INITIAL MASS?

- Repeat for clusters of different ages (and hence RSGs of different initial masses..)
A MASS-DEPENDENT MASS-LOSS RATE PRESCRIPTION

Same gradient to within the errors...

Beasor et al. (2020)
A MASS-DEPENDENT MASS-LOSS RATE PRESCRIPTION

Beasor et al. 2020
COMPARISON TO OTHER PRESCRIPTIONS

Beasor et al. 2020

Lower scatter
No offset

Scatter slightly higher
Avg offset = 0.13
BUT much worse for higher luminosity stars…
**COMPARISON TO EVOLUTIONARY MODELS**

Solid line - current implementation

Dashed line - our prescription

Quiescent mass-loss *cannot* remove the H envelope....
What does it all mean...

- Observed H-poor SN fraction ~ 1/3
- Back of the envelope IMF calculation...

% stars 8-30M⊙ ~ 85%
% stars >30M⊙ ~ 15%
If mass-loss rates were higher... could explain this discrepancy

% stars 8-16M$_\odot$ $\sim$ 60%
% stars $>$16$\odot$ $\sim$ 40%

Core-Collapse SN Fractions
Smith et al. 2011
What does it all mean...

- But, mass-loss rates are **lower**
- Single star evolution cannot explain the observed SN rate
- Strong evidence for **most H-poor SN being the products of binary interaction**

![Pie chart showing SN fractions: H-poor 48.2%, II-P 6.4%, II-n 8.8%](chart)

Core-Collapse SN Fractions

Smith et al. 2011
**CONCLUSIONS: Part 1**

- There is no observationally motivated reason to increase mass-loss by factors of 3 or more in stellar evolution models.

- RSGs that evolve as single stars *do not* shed their envelope via quiescent mass loss.

- Single stars between 20-30$M_\odot$ *do not* lose enough mass to evolve blueward.

- The relative number of stripped/unstripped SN events predicted by single star models is way off.

- Something else (binaries??) is removing the envelope.
HOW WELL DO WE KNOW CLUSTER AGES?
USING THE CMD

- For old and intermediate age clusters (>50Myr), many observational effects can’t be explain by SSP…
- e.g. blue stragglers

Bastian et al. 2018
CMD of NGC 7419

- MSTO
- RSGs

Included • Not included
METHOD 1: brightest TO star
METHOD 2: luminosity function of the TO

Slightly more robust?
METHOD 3: lowest luminosity RSG

The diagram shows evolutionary tracks for non-rotating and rotating massive stars. The tracks are labeled with masses in solar units (M☉). The horizontal axis represents the logarithm of the effective temperature (log T$_{\text{eff}}$) divided by 38, while the vertical axis represents the logarithm of the luminosity (log L/L$_\odot$) divided by 38.

- **Non-rotating models** are represented by dotted lines.
- **Rotating models** are represented by continuous lines.

The tracks start at various masses and extend to different luminosities, characterizing the evolution of stars from the Main Sequence to the Red Supergiant (RSG) phase. The Z = 0.020 metallicity level is indicated, showing how different masses evolve under rotation.

**Key Points**:
- The tracks for rotating models have higher luminosities due to the effect of rotation.
- The mass at which the star enters the RSG phase (i.e., the red supergiant phase) is significantly affected by rotation.
- The higher luminosity implies that the star spends less time at the RSG phase compared to non-rotating models.
- Rotation affects the mass loss rates, preventing the formation of a large intermediate convective zone and thus favoring a rapid evolution to the Wolf-Rayet phase.

**Additional Observations**:
- The behavior of the rotating models is compared with non-rotating models through formulas proposed by Friend & Abbott (1986).
- The effect of rotation on the mass-luminosity relation is discussed, with rotation increasing the lifetimes of stars and leading to higher luminosities.

**References**
- Herrero et al. (2000)
- Herrero et al. (2000a)
- Herrero et al. (2000b)
- Herrero et al. (2000c)
Big disagreement in ages between the methods

This is seen for all clusters in our sample
What’s going on...?

Rotation can’t explain the offset... $v/v_{\text{crit}} = 0.95$ is really really fast.

Mergers???

- 20myr, $v/v_{\text{crit}} = 0$
- 20myr, $v/v_{\text{crit}} = 0.95$
- 10myr, $v/v_{\text{crit}} = 0$
Testing with synthetic clusters... - single stars

Single stars only. TO method underestimates the age by quite a lot
Testing with synthetic clusters...
- binary fraction of 50%

Binary fraction of 50%.
Even worse for TO...
RSGs do better.
CASE STUDY: Westerlund 1

Supposedly a very young Galactic cluster (~4Myr), and massive (10^5 Msun).

Beasor et al. (submitted)
CASE STUDY: Westerlund 1

First time we’ve been able to attempt a bolometric luminosity for these RSGs...
CASE STUDY: Westerlund 1

Beasor et al. (submitted)
CONCLUSIONS: Part 2

- Using the cluster turn-off to estimate age will cause ages to be underestimated.
- Using red supergiants allows a binary independent age to be determined.
- There could be lots of mergers/mass transfer systems in young clusters.
- Westerlund 1 probably isn’t as young as people first thought.