The Effects of Rotation in Starburst99 Models

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- HRD from Ekström et al. (2012)
- Hot, massive vs. cool, less massive stars
- Hot: all stages of evolution matter
- Cool: late stages of evolution matter
- Hot: atmospheres relatively well understood
- Cool: atmospheres are quite uncertain
- Stellar structure and evolution of massive stars is a major challenge
Why do we need a new generation of evolution models?

What is different in the models?

How do they compare with data?
HRD from Hamann & Koesterke (2000)

**Conti scenario** (Conti 1976): WR stars are low-mass, enriched descendants of O stars

- O stars have strong stellar winds
- \( \frac{dM}{dt} \approx 10^{-5} \, M_\odot \, yr^{-1} \); \( t = 5 \, Myr \rightarrow \) lose 50 \( M_\odot \)
- Expose He, N, C-rich core
- O star → WR star

.... the golden (gilded) age of massive-star research
Smith (2009)

Stellar winds of hot stars are highly inhomogeneous

Mass-loss rates of OB stars are overestimated by factors of 5!

How do OB stars lose their mass?
- Hunter et al. (2009): N/H and $v$ sin $i$ in LMC B stars
- Significant **N enrichment** on the main sequence
- Rotation must be important
Brott et al. (2011): evolutionary models with rotation

1. $M < 2 M_\odot$: rotation negligible because of magnetic braking
2. $2 M_\odot < M < 15 M_\odot$: $T_{\text{eff}}$ decrease caused by centrifugal forces
3. $M > 15 M_\odot$: larger convective core with higher $T_{\text{eff}}$ and $L$
Ekström et al. (2012): full set of evolution models with rotation

- $0.8 \, \text{M}_\odot < M < 120 \, \text{M}_\odot$
- $Z = \text{Z}_\odot$
- $v_{\text{rot}} = 0.4 \, v_{\text{breakup}}$ on ZAMS
- Calibrated extensively via local stars and star clusters
- Implemented in Starburst99 v7.0 (Leitherer et al. 2014)
Leitherer et al. (2014)

- UV to near-IR SED of standard SSP
  - $Z = Z_{\odot}$ and $1/7^{th}$ $Z_{\odot}$
Models with rotation are more luminous by ~0.4 mag because of the higher L/M and \( T_{\text{eff}} \) of individual stars.
The number ionizing photons increases by a factor of ~4 when hot, massive stars are present.
Hα equivalent width vs. time (continuous SF, Z⊙, Kroupa IMF)

- W(Hα) increases by ~0.2 dex. If used as an IMF indicator in late-type galaxies, the new models change the IMF exponent from, e.g., 2.3 to 2.6
\( \text{Br} \gamma \text{ luminosity vs. time} \) (SFR = 100 M\( _{\odot} \) yr\(^{-1} \), Z\( _{\odot} \), Kroupa IMF)

- Applied to IR-luminous galaxies: models with rotation lead to, e.g., SFR = 100 M\( _{\odot} \) yr\(^{-1} \), whereas models without give SFR = 175 M\( _{\odot} \) yr\(^{-1} \).
CO index vs. time \((\text{SSP}, 10^6 \, M_\odot, \text{Kroupa IMF})\)

- Thick solid: \(Z_\odot\), no rotation; thick dashed: \(Z_\odot\), rotation
- Thin solid: \(1/7 \, Z_\odot\), no rotation; thin dashed: \(1/7 \, Z_\odot\), rotation
EW(4686) vs. time \((SSP, 10^6 M_\odot, \text{Kroupa IMF})\)

- Thick solid: \(Z_\odot\), no rotation; thick dashed: \(Z_\odot\), rotation
- Thin solid: \(1/7 Z_\odot\), no rotation; thin dashed: \(1/7 Z_\odot\), rotation
Implemented W-R library in Starburst99 using PoWR models available at http://www.astro.physik.uni-potsdam.de/~wrh/PoWR/powrgrid1.html
- UV spectrum of evolving SSP at different epochs
- Blue: no rotation
- Red: with rotation
- WR stars show several detectable features in addition to He II $\lambda$1640
Comparison with SDSS DR7

- Geneva tracks were calibrated via stellar data in the Local Group (e.g., WR/O/RSG); affected by small-number statistics (e.g., 12 WR stars in SMC)
- Here: use integrated galaxy data from SDSS DR7
- Identify all WR galaxies via He II 4686 (Agienko et al. (2013))
- $2.2 \text{ Mpc} < D < 650 \text{ Mpc}$
- $7.2 < \log O/H +12 < 8.7$ ($T_e$ and $R_{23}$)
- ~280 galaxies
He II $\lambda 4686$ SDSS vs. models
C IV λ5808 SDSS vs. models
- Solar chemical composition: both rotating and non-rotating models agree with WN population.
- Solar chemical composition: SDSS data favor rotating models for WC stars.
- Subsolar composition: both rotating and non-rotating models grossly underpredict WR stars.
- Subsolar models predict many hot stars but they are not chemically enriched → no WR stars.
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Hint: all 12 WR stars in the SMC are binaries....
Rapid rotators from binaries

1. Tides in close binaries

2. Spin up by mass transfer

3. Mergers?

About 10% of all stars are expected to merge with a companion as a result of binary evolution

(Podsiadlowski+ Portegies Zwart+)

For massive stars as high as 25%?

(Sana, De Mink et al. 2011)

e.g. Podsiadlowski+90, Suzuki+07, Gaburov+08, Glebbeek+09
Sana et al. (2012): evolutionary channels of massive close binaries
de Mink (2012): simulated rotation velocity distribution

- Magenta: single
- Cyan: interacting
- Yellow: spin-up
- Blue: merger
Eldridge & Stanway (2009): rejuvenation effect in SSP

- Evolution of H\(\beta\) equivalent width with time in SF galaxy
- Solid: single stars with different Z; dashed: binaries with different Z
- Hot, ionizing population appears after \(\sim 10\) Myr
- Relevance: age spread of star formation? LINERs?
Take-Away Points

- Stellar evolution is a major uncertainty in modeling populations of massive stars.
- The latest generation of evolution models is drastically different from the previous one.
- Stellar mass loss, rotation and binarity all affect evolution and are difficult to distinguish empirically.
- The uncertainties increase with decreasing wavelength and can reach a factor of several in the Lyman continuum.