Including WR, TP-AGB, and Binary Stars in Population Synthesis Models

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### Z/Y (PARSEC tracks)

<table>
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<tr>
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<tbody>
<tr>
<td>0.0000/0.230</td>
<td>0.0001/0.249</td>
<td>0.0002/0.249</td>
<td>0.0005/0.249</td>
<td>0.001/0.250</td>
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<tr>
<td>0.002/0.252</td>
<td>0.004/0.256</td>
<td>0.006/0.259</td>
<td>0.008/0.263</td>
<td>0.014/0.273</td>
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<tr>
<td>0.017/0.279</td>
<td>0.010/0.267</td>
<td>0.020/0.284</td>
<td>0.030/0.302</td>
<td>0.040/0.321</td>
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- Fine grid of stellar mass from 0.10 to 400 Mo
- Usually > 26,000 points in the HRD per Z

**PARSEC Evolutionary Tracks:**

- **PA**dova & **TR**ieste **S**tellar **E**volution **C**ode by:
  - Chen et al. (2015) for massive stars up to 350 Mo **(WR phase)**
  - Bressan et al. (2012) for lower masses **(includes TP-AGB treatment)**
Stellar Spectra

- WM-Basic (Leitherer+ 2010) for MS stars hotter 20,000K
- Tlusty models (Lanz & Hubeny, 2003+2007) for O and B stars
- PoWR models (Gräfener+ 2002, Hamman+ 2004) for WR stars
- MILES (Sánchez-Blázquez+ 2006) in available range
- IRTF (Rayner+ 2009) for cool giants
- Aringer+ 2009 models for C stars
- DUSTY Code (Ivezic+ 1999) as in González-Lopezlira+ 2010 for TP-AGB

Binary star evolution computed with the BSE code by Hurley+ 2002 (see Hernández-Pérez & Bruzual 2013, 2014 for details)
PoWR - The Potsdam Wolf-Rayet Models

- High resolution models

  Hainich et al. (2015)

  Todt et al. (2015, private communication)

- WC, WNE, WNL, WO types

- $Z/Z_0 = 1$ (MW), 0.5 (LMC), 0.2 (SMC), 0.07 (sub-SMC)

- Wavelength coverage: 200 - 80,000 A, resolution 0.30 A
WC model for $T_{\text{eff}} = 79,000$ K, $\log R_{\lambda}/R_{\odot} = 0.50$
CB13, Z=0.014, SSP, 5 Myr

- Total
- MS
- WNL
- WNE
- WC
- WO
CB13, Z=0.014, SSP, 6 Myr

$M_u = 600 \ M_\odot$

$M_u = 100 \ M_\odot$

Total
MS
WNL
WNE
WC
WO
TP-AGB stars
Padova 2012–2013: $Z = 0.008$, $M = 0.75 - 5.60 \, M_\odot$

TP-AGB: O-Rich
Padova 2012–2013: $Z = 0.008, M = 0.75 - 5.60 \, M_\odot$

TP-AGB:
O-Rich
C-Rich
SW-phase
LMC TP-AGB LF, CB13, Z = 0.008, SET-1 (top) vs SET-2 (bottom), HR dusty models

\[ \frac{O}{M} = 24114/30970 \]
\[ D(K) = -0.106 \]
\[ \text{O-rich: Tracks} \]
\[ \frac{O}{M} = 17880/19453 \]
\[ D(K) = -0.106 \]
\[ \text{O-rich: Color} \]
\[ \frac{O}{M} = 17843/12621 \]
\[ D(K) = -0.106 \]
\[ \text{C-rich: Tracks} \]
\[ \frac{O}{M} = 6234/11517 \]
\[ D(K) = -0.106 \]
\[ \text{C-rich: Color} \]
\[ \frac{O}{M} = 6271/18349 \]
\[ D(K) = -0.106 \]
<table>
<thead>
<tr>
<th>Type</th>
<th>Tracks O/M</th>
<th>Tracks D(K)</th>
<th>Color O/M</th>
<th>Color D(K)</th>
<th>Tracks O/M</th>
<th>Tracks D(K)</th>
<th>Color O/M</th>
<th>Color D(K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All TP-AGB</td>
<td>5738/22865</td>
<td>-0.598</td>
<td>3705/12422</td>
<td>-0.598</td>
<td>3558/9124</td>
<td>-0.598</td>
<td>2033/10443</td>
<td>-0.598</td>
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<tr>
<td>O-rich</td>
<td>3705/12422</td>
<td>-0.598</td>
<td>3558/9124</td>
<td>-0.598</td>
<td>2033/10443</td>
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<td>2180/13741</td>
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<tr>
<td>C-rich</td>
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<td>-0.398</td>
<td>3705/10897</td>
<td>-0.398</td>
<td>3558/5678</td>
<td>-0.398</td>
<td>2033/3523</td>
<td>-0.398</td>
</tr>
</tbody>
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SMC TP-AGB LF, CB13, Z = Zmix, SET-1 (top) vs SET-2 (bottom), HR dusty models
Including binary star evolution in PS models

Motivation: UVX in Early Type Galaxies

Use the Hurley et al. (2002) code to compute the evolution of binary stars in the HRD.

Hernández-Pérez & Bruzual (2013, 2014)
Stochastic sampling of IMF

- Important for low mass stellar populations
- Fluctuations dominate number of stars in short lived stellar evolutionary phases
Stochastic sampling of Chabrier IMF, $t=1$ Myr, $Z = Z_0$.

Cluster mass ($M_\odot$):

- $10^2$
- $10^3$
- $10^4$
- $10^5$
- $10^6$

$M_\odot$ = standard model
Stochastic sampling of Chabrier IMF, $M=5000 \, \text{M}_{\odot}$, $t=1 \, \text{Gyr}$, $Z = Z_{\odot}$
Stochastic sampling of IMF + binary star evolution

Z=0.02, Kroupa IMF, BF=0.50

M=10^3 M_☉  HB13+CB13 stochastic

CB13 stochastic

Z=0.02, Kroupa IMF, BF=0.50

M=10^4 M_☉

Z=0.02, Kroupa IMF, BF=0.50

M=10^5 M_☉
Stochastic sampling of IMF + binary star evolution

\[ Z=0.02, \text{ Kroupa IMF, BF}=0.50 \]

- \( M=10^3 M_\odot \)
  - HB13+CB13 stochastic
  - CB13 standard
  - 0.5 Gyr
  - 1 Gyr
  - 5 Gyr
  - 12 Gyr

- \( M=10^4 M_\odot \)

- \( M=10^5 M_\odot \)
Stochastic sampling of IMF + binary star evolution

Z=0.02, Kroupa IMF, BF=0.50

M=10^3M_\odot

HB13+CB13 stochastic

CB13 stochastic

M=10^4M_\odot

M=10^5M_\odot

0.0 0.5 1.0 1.5 2.0

g−r [AB mag]

0.0 0.5 1.0 1.5

r−i [AB mag]
Stochastic sampling of IMF + binary star evolution

- Standard model
- Selected age: 0 < t < 14 Gyr
- Stochastic model
- Stochastic sampling of IMF + binary star evolution
Conclusions

- Prospects are good both at the UV and NIR ends
- Considerable progress in evolutionary tracks and spectral libraries
- Lots of observations have allowed to improve calibration of SPS models
- Stochastic fluctuations and binary evolution play an important role in photometric properties of stellar populations, especially in low mass systems
- It is important to take these effects into account in PSM’s and not extrapolate behaviour of infinite mass models to low mass