Stellar Evolution &
issues related to the post Turn-Off evolution

Santi Cassisi

INAF - Astronomical Observatory of Teramo, Italy
The point of view of Population Synthesis users

What do they want?

Magnitudes & Colors
Spectral indices
Integrated spectra
Surface Brightness fluctuations

Stellar models provide:

• Evolutionary lifetimes
• Bolometric luminosity
• Effective temperature
• Actual Mass

What do you need?

Bolometric corrections + color-$T_{\text{eff}}$ relations + spectral library
Color-Magnitude diagrams of star clusters: laboratories of low- & intermediate mass stellar evolution

Rood et al. (1998)
Issues related to post-TO evolution

• What is a “realistic” estimate of the uncertainty affecting SMs in advanced evolutionary stages?

• How do these uncertainties affect the Pop. Synthesis predictions and the calibration of distance indicators?

• The most critical issues...
  • Mass loss efficiency during the RGB and AGB stages;
  • Extremely Hot HB stars;
  • The reliability of AGB stellar models;
Input physics affecting the RGB models

**Input**

- Equation of State
- Low Temperature Radiative Opacity
- Efficiency of the convective energy transport
- Boundary conditions
- Abundances (He, Fe & $\alpha$-elements)
- Conductive Opacity
- Neutrino energy losses
- Atomic diffusion efficiency

**Evolutionary properties**

- $\Delta T_{\text{eff}} \sim 100K$
- $\Delta T_{\text{eff}} \sim 150K$
- $\Delta T_{\text{eff}} \leq 80K$

Evolutionary properties:

- $T_{\text{eff}}$
- RGB location & shape
- He core mass@RGB Tip
- RGB Tip brightness
Models from different libraries, based on a solar-calibrated $m_l$, can show different RGB effective temperatures. The difference can be also larger (up to 400K) when accounting for "old" stellar models.

Is there any way to check the reliability of RGB stellar models?
Eclipsing binary: an important benchmark

When the distance & the metallicity are known the degrees of freedom in the fitting procedure are drastically reduced...

Photometry by Stetson et al. (2003)

\[(m-M)_V = 13.46 \pm 0.10\]

\[E(B-V) = 0.15 \pm 0.02\]

Kalirai et al. (2007)
What is the impact on PS predictions?

Some quantitative tests of the sensitivity to RGB/AGB stars

- Red triangles $\Rightarrow T_{\text{eff}} + 100$ K (only the AGB & RGB)
- Blue circles $\Rightarrow \log(g) + 0.25$ dex
- Asterisks $\Rightarrow [\text{Fe/H}] \pm 0.15$ dex
- Open triangles $\Rightarrow T_{\text{eff}} + 100$ K (whole isochrone)

![Graph showing the impact on PS predictions with various symbols and annotations.](image-url)
The RGB Tip brightness: a standard candle

The I-Cousins TRGB magnitude is one of the most important primary distance indicators (Tamman+08):

- age independent for t>2-3Gyrs;
- metallicity independent for [M/H]<-0.9

In the last few years, thanks to the ACS@HST, it has been measured in many galaxies outside the Local Group (Caldwell 06, Rizzi+06, Mager+08,…)

empirical calibrations

NGC300: Rizzi+06

RGB tip
The future: JWST and/or ELT+AO

Both the best observational facilities of the future will be optimized for the near infrared.

JWST should “see” also the I band.

The Red Giant Branch is what we will see of resolved giant ellipticals!

Is its calibration still a critical issue?
Updated RGB models are now in agreement with empirical data at the level of better than 0.5σ.

The TRGB brightness: theoretical calibration

In the near-IR bands, the same calibration seems to be in fine agreement with empirical constraints (but in the J-band...)

If you want to use the Tip as a distance indicator for elliptical galaxies it is better to use NIR passbands.
Input physics affecting the HB3 models

Input

• Equation of State
• Low Temperature Radiative Opacity
• Efficiency of the convective energy transport
• Boundary conditions
• Abundances (He, Fe & \(\alpha\)-elements)
• Conductive Opacity
• Neutrino energy losses
• Atomic diffusion efficiency
• Mass loss efficiency

Evolutionary properties

\(T_{\text{eff}}\)

- RGB location & shape

He core mass@RGB Tip

- RGB Tip brightness

Envelope mass
The impact on the Horizontal Branch morphology

Mass loss has negligible (…not always…!) effects on the evolutionary properties of RGB stars, but it strongly controls the color distribution of stars along the Horizontal Branch.

Warning: we can not predict “a priori” the HB morphology for a given metallicity!!!!

Conroy et al. 2009
The "HB type" strongly affects the integrated colors and magnitudes. This should be seriously taken into account when interpreting color differences among GCs in the same galaxy as "just" due to a metallicity differences \(\rightarrow\) color bimodality, color-(UV) color diagram, "integrated" GCs CMD

Mieske et al.(2008)
The HB morphology versus Spectral indices

An “hot” HB increases the strength of the Balmer lines and can make an old population looks spuriously young (Lee+00, De Propris 00)!

In their seminal work, Lee et al (00) assume that the change of the HB type is driven by age…but…

Percival & Salaris (2011)
The Asymptotic Giant Branch

The AGB evolutionary stage is crucial:

- Population tracers
- Integrated properties of resolved & unresolved stellar populations

Surface Brightness Fluctuations

Lee, Worthey & Blakeslee (2009)

Age = 0.5, 1, 5, 13 Gyr
Z = 0.0003, 0.004, 0.008, 0.02, 0.04

with TP-AGB
without TP-AGB

≈2 mag

Marigo et al. (2008)
The AGB stage treatment in Pop. Synthesis Tools

Models (for Z=0.01) by:

✓ Maraston (2005)
✓ Marigo & Girardi (2008, Padua)
✓ Percival et al. (2009, BaSTI) (also for Z=0.008, 0.004, 0.0008)
AGB stellar models

Nucleosynthesis

Brightness

Effective temperature scale → colors

Evolutionary lifetime

Initial - Final mass relation
The efficiency of the Third Dredge Up

Helium, Carbon, s-elements ↑

The mixing efficiency during the TDU has important effects on:

- the rate of surface C-enhancement;
- the effective temperature scale and colors;
- the mass loss efficiency and, in turn, the TP stage lifetime;
- the nucleosynthesis;
The opacitive effects of the $C$-enhancement

Scalo & Ulrich (1975) and Marigo (2002) showed that: TiO and $H_2O$ are the most important molecules in the oxygen-rich regime ($C/O<1$), while carbon-bearing molecules ($C_2$, CN, $C_2H_2$ and $C_3$) dominate the opacity for $C/O>1$.

Fundamental further steps ahead have been now made by Lederer & Aringer (2008), Marigo & Aringer (2009) and by Weiss & Ferguson (2009).

What is the impact on the effective temperature scale?
The importance of an appropriate treatment of C-rich mixture opacity

Direct effect:
• huge decrease of the effective temperature
• huge increase of the mass loss efficiency...
• reduction of the Hot Bottom Burning efficiency...

Indirect effect:
• strong increase of the mass loss efficiency...
• reduction of the Hot Bottom Burning efficiency...

Marigo & Girardi (2007)
AGB stellar models: the neverending story…

AGB models are based on the fine-tuning of many free parameters!

So they have not to be taken as a “dogma”: an illustrative case…

- The new “Padua” (MG07) AGB models were announced as quite reliable and accurate…;
- So many groups have recomputed their pop. Syn. Models by using these updated prescriptions;
- BUT, after a while, it was evident that such models overestimate the AGB flux contribution, due to the too long evolutionary lifetimes…

Girardi et al. (2011)