Current uncertainties in low- and intermediate-mass star models

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Fine-Tuning Stellar Population Models
Leiden, 26-30 June 2006
The point of view of Pop. Synthesis builders
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The evolutionary stellar models provide:

- **Evolutionary lifetimes** ⇒ **Star counts**

- Bolometric luminosity

- **Effective temperature**

- Mass – different than the initial one (!)
The point of view of Pop. Synthesis builders

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Gravity

$T_{\text{eff}}$

Bolometric correction(s) +
color-$T_{\text{eff}}$ relations
The point of view of Pop. Synthesis builders

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T_{eff}

Bolometric correction(s) + color-T_{eff} relations

Magnitudes & Colors

How much reliable & accurate are theoretical predictions?
Stellar evolution models: the ingredients
Stellar evolution models: the ingredients
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- The stellar structure equations
  - Surface boundary conditions
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- The physical inputs:
  - Equation of state
  - Opacity
  - Nuclear cross sections
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- **The microscopic mechanisms:**
  - Atomic diffusion
  - Levitation
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- The microscopic mechanisms:
  - Atomic diffusion
  - Levitation

- The macroscopic mechanisms:
  - Convection
  - Overshooting
  - Mixing processes during the core He-burning phase
  - Mixing during the AGB phase
  - Mass loss
Old stellar populations

The core H-burning phase: the **Main Sequence**

What we know and what we would like to know better...
Old stellar populations

The core H-burning phase: the Main Sequence

What we know and what we would like to know better…
The comparison between “real” CMDs and synthetic ones provide strong constraints on the Star Formation History (SFH).

The Main Sequence locus is one of the “best” evolutionary sequences for retrieving the SFH.

This is possible if theoretical predictions about the MS location and evolutionary lifetimes are accurate.
The Age - Luminosity relation

Input physics affecting the theoretical calibration:

- Equation of State $\rightarrow$ luminosity – effective temperature
- Opacity $\rightarrow$ luminosity – effective temperature
- Nuclear reaction rates $\rightarrow$ luminosity
- Efficiency of the convective energy transport $\rightarrow$ effective temperature
- Abundances (He, Fe & $\alpha$-elements) $\rightarrow$ luminosity – effective temperature
- Microscopic diffusion $\rightarrow$ luminosity – effective temperature
- Boundary conditions $\rightarrow$ effective temperature
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Is the metallicity of the Sun really “solar”?
The nuclear cross-sections for H-burning
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The nuclear cross-sections for H-burning
The onset of the CNO cycle

The $^{14}$N(p,γ)$^{15}$O reaction starts to become important!

This reaction is the “bottleneck” of the CNO cycle and regulates the release of energy and the H consumption.
Implications for the age calibration
Implications for the age calibration

The LUNA experiment (Formicola et al. 03) has significantly improved the low energy measurements of this reaction rate, decreasing its value of a factor of $\sim 2$ with respect previous estimates.

This new calibration provides ages systematically older by 0.7 and 1Gyr.
The solar heavy elements mixture

Recent analyses (Asplund et al. 04) based on 3-D model atmospheres suggest that solar abundances of O and other heavy elements are reduced in comparison to previous estimates.

\[(Z/X)_\odot \text{ (Asplund et al. 04)} = 0.0165 \iff (Z/X)_\odot \text{ (Grevesse & Sauval 98)} = 0.0231\]
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\[Z^* \sim Z_{\odot} \times 10^{[M/H]} \quad \Rightarrow \quad Z_{\text{NEW}} \sim 0.65 \times Z_{\text{OLD}}\]

For a fixed $M_v$(TO) & $[M/H]$, the cluster age increases by about 0.7 Gyr ...
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For a fixed \( M_v(\text{TO}) \) & \([M/H]\), the cluster age increases by about 0.7Gyr ...
• At a given TO brightness, the difference are lower than ~1Gyr (but in the case of the Yale isochrones... this could be due to reasons other than the input physics...)

• This difference can be partially accounted for by considering the different initial He content and physical inputs
Old stellar populations

The shell H-burning phase: the Red Giant Branch
Old stellar populations

The shell H-burning phase: the Red Giant Branch

The RGB is one of the most prominent and well-populated features in the CMD of stellar populations older than about 1.5-2Gyr
Old stellar populations

The shell H-burning phase: the Red Giant Branch

The RGB is one of the most prominent and well-populated features in the CMD of stellar populations older than about 1.5-2Gyr.

RGB stars provide a major contribution to the integrated bolometric magnitude and to the integrated Near-Infrared colors and spectra of old distant, unresolved, stellar population.

The RGB location and shape are strongly sensitive to the metallicity.

A correct theoretical prediction of the RGB properties is of paramount importance for interpreting empirical data of distant star clusters and galaxies using population synthesis tools but also for estimating the properties (age, Z,...) of resolved galactic clusters by means of isochrone fitting techniques.
Input physics affecting the RGB location & shape

- Equation of State
- Low Temperature Opacity
- Efficiency of the convective energy transport
- Boundary conditions
- Abundances (He, Fe & $\alpha$-elements)

Mass loss efficiency: how to treat it in stellar model computations?
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Mass loss efficiency: how to treat it in stellar model computations?
Models from different authors, based on a solar-calibrated $ml$, can show different RGB effective temperatures. This is probably due to some differences in the input physics, such EOS and/or boundary conditions which is not compensated by the solar recalibration of the $ml$. 

Red Giant Branch models: the state of art
Mass loss along the RGB

The impact of mass loss phenomenon on the evolutionary properties of RGB stars is (...not always!...) negligible, but...this is not the case when considering the contribution of the Horizontal Branch phase to the integrated properties of a stellar population...
Mass loss along the RGB

The impact of mass loss phenomenon on the evolutionary properties of RGB stars is (...not always!...) negligible, but...this is not the case when considering the contribution of the Horizontal Branch phase to the integrated properties of a stellar population...

For a fixed He core mass, the lower the envelope mass the hotter the HB location...
Strong dependence on the photometric band...

High mass-loss efficiency

low mass-loss efficiency
Knowledge of how RG stars lose mass is one of the necessary prerequisites for understanding the properties of HB stars, such as: their color distribution, the variation of HB morphology with metallicity.
Investigations of the impact of RGB mass loss upon the HB morphology have mostly relied on the Reimers's (1975) formula, and it is widely used as a “LAW”! (see also Catelan 2005)

But...
Mass loss on the RGB: an (in)famous “unknown”

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But…

![Image of a graph showing mass loss vs. metallicity (Fe/H) for various models. The graph includes data from Reimers, Modified Reimers, Mullan, Goldberg, Judge-Stencel, and VandenBerg models, with the x-axis representing [Fe/H] and the y-axis representing $\Delta M_{\text{RGB}} (M_\odot)$]
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But...

None of the currently available analytical formulae is able to reproduce the mass-loss rate measured by Origlia et al. (2002)...
Old stellar populations
Old stellar populations

The core He-burning phase: the Horizontal Branch

Main (longstanding) problems:

**The luminosity** → standard candle

Sources of uncertainty:
- Conductive opacity
- Atomic diffusion efficiency

**The evolutionary lifetime** → the star counts

Sources of uncertainty:
- Mixing scheme
- The $^{12}C(\alpha,\gamma)^{16}O$ reaction rate

**The morphology** → the $2^\circ$ parameter
Young & intermediate-age stellar populations
Young & intermediate-age stellar populations

NGC1866
Young & intermediate-age stellar populations

Core H-burning phase
Young & intermediate-age stellar populations

Core H-burning phase

Core He-burning phase
Young & intermediate-age stellar populations

The electron degeneracy is always negligible (but during the Asymptotic Giant Branch phase);

Non ideal effects, such as coulomb interactions, are quite negligible

Radiative opacity is not affected by a large uncertainty as for very cool structures
Open problems …

The extension of the convective core (CC) during the H-burning phase:

Is the size of the CC, as determined by the (classical) Schwarzschild criterion able to properly fit the observations, or it must be “artificially” increased?

This long standing problem has always been (unfortunately) interpreted in terms of “overshooting” ⇒ a proof of the existence or non existence of a specific phenomenon where the convective cells cross the classical border of the CC

this is not entirely appropriate!

If observations show that the CC has to be larger than predicted by canonical models, various causes can be considered:

- “True” overshooting (Barmina et al. 02)
- Uncertainty in the radiative opacity (Iglesias & Rogers 96)
- Rotation (Maeder & Meynet 01)

overshoot ⇔ whatever, not well defined, mechanism(s) able to increase the CC size
The effects of overshooting

- The core H-burning lifetime is longer;
- The size of the He core at the end of the central H-burning phase is larger;
- The mean luminosity during the core He-burning phase is larger;
- The central He-burning lifetime is shorter;
- The critical masses $M_{\text{HeF}}$ and $M_{\text{up}}$ are significantly reduced;
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- The size of the He core at the end of the central H-burning phase is larger;
- The mean luminosity during the core He-burning phase is larger;
- The central He-burning lifetime is shorter;
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<table>
<thead>
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<th>$\lambda$</th>
<th>$t_H(\text{Myr})$</th>
<th>$t_{\text{He}}(\text{Myr})$</th>
<th>$t_H/t_{\text{He}}$</th>
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<td>19.9</td>
<td>4.3</td>
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<tr>
<td>0.25</td>
<td>100.1</td>
<td>10.0</td>
<td>10.0</td>
</tr>
</tbody>
</table>

The theoretical framework for intermediate-mass stars is strongly affected by the adopted assumption about convective core overshooting.
The **Asymptotic Giant Branch**
The Asymptotic Giant Branch

The AGB evolutionary phase is very important for many reasons as:

- The nucleosynthesis → pollution of GC stars
- Population tracers
- Integrated colors of resolved & unresolved stellar populations

see also the talk by Claudia Maraston
The Asymptotic Giant Branch

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- Nucleosynthesis → pollution of GC stars
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- Integrated colors of resolved & unresolved stellar populations

See also the talk by Claudia Maraston.

Nucleosynthesis
- Effective temperature scale → colors
- Mass loss →
  - Evolutionary lifetime
  - Initial – final mass relation

[Diagram showing the Asymptotic Giant Branch with labeled components such as mass coordinate, time, nuclear burning, mass loss, mixing process, opacity, and a graph showing the effective temperature scale.]
The Third dredge up (TDU)

Problem: How to treat the mixing during the TDU?

Solution(s):
- Bare Schwarzschild criterion
- Envelope overshoot
- Time dependent mixing
- Diffusive process

Free (!) parameter(s)
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Important consequences...

M Stars – C/O<1 – Smith & Lambert 90
S Stars – C/O~1 – Ohnaka & Tsuji 96
C Stars – C/O>1 – Lambert et al. 86 + Ohnaka et al. 00

To not account for the enhancement of C during the TDU causes that AGB models are not able to reproduce the $T_{\text{eff}}$ of C stars.
Important consequences...

A strong impact on the (Near Infrared) colors of AGB stars has to be expected...
Conclusions
Conclusions

“Nothing is perfect!!!”

Gustavo quoting Claudia
Conclusions
Conclusions

Can I trust Stellar evolutionary models cooks?
Conclusions
Conclusions

An illustrative case (see talk by A. Aparicio: The dwarf galaxy Phoenix

Courtesy of S. Hidalgo & A. Aparicio
Conclusions

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Conclusions

Courtesy of S. Hidalgo & A. Aparicio

Padua library (Bertelli et al. 94)

BaSTI library –old release (Pietrinferni et al. 04)

BaSTI library –new release (Pietrinferni et al. 06)