Fine-tuning stellar models: steps towards calibrated calculations

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What do you want?

- stellar models (global properties)
- all masses
- all compositions
- all evolutionary phases
- dense grids (for accurate interpolation)
- homogeneous physics
- accurate models
- reliable models
- models that give you “nice” results
What do you get?

- stellar models
- all masses
- all compositions
- all evolutionary phases
- dense grids
- homogeneous physics
- accurate models
- reliable models

- plenty from everywhere
- sometimes restricted
- standard compositions
- AGB? late phases?
- possibly
- today almost, but not really
- within code capabilities
- how should one know?

- you could also get interior structure and chemical yields
Basic requirements

- for any specified physical assumption
  - microphysics (opacities, equation of state, neutrino emission, diffusion coefficients, ...)
  - physical effect (overshooting, rotation, mass loss)

  models should be unique and not depend on the source

- differences in the models can be traced back to differences in these physical details, and not be due to code specifics

- technical code development should not alter the results

  present stellar evolution codes do not fulfill these requirements

- implication: the choice of the source for the models may determine your result, not the choice of the model physics
The Solar Model

- solar models suffered from the same problem
- but it was solved (GONG initiative)

sound speed of three solar models (Princeton, Århus, Garching) agrees within 0.001 over 80% of solar radius. Others have followed (Padova, Yale, ...)

to achieve this, you may have to worry about details like table interpolation
Asteroseismology

• same problem:
  - predicted oscillation frequency should depend on physical assumption
  - want to learn about stellar physics (diffusion, rotation, convection) and determine stellar parameters (mass, age)

• much higher requirements
  - complete internal structure
  - high sensitivity of mode frequencies
  - depend on derivatives of physical quantities, not only on values

• restricted parameter range

• some stellar quantities known
COROT/ESTA

- COROT working group
- Evolution and Seismic Tools Activity (ESTA)
- regular meetings
- comparison of stellar evolution and oscillation frequency codes and models
- definition of set of standard cases with standard physical assumptions
- task 1: stellar models – mostly completed
- task 2: pulsation frequencies – 2006
- codes: Århus, CESAM, CLES, Franec (Pisa), TGEC, Starox, Garstec, ...
## ESTA task 1 cases

<table>
<thead>
<tr>
<th>case</th>
<th>mass</th>
<th>Y0</th>
<th>Z0</th>
<th>Xc</th>
<th>Tc</th>
<th>M\textsubscript{He core}</th>
<th>overshoot</th>
<th>phase</th>
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<tr>
<td>1.1</td>
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<td>0.02</td>
<td>0.35</td>
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<td>1.2</td>
<td>1.2</td>
<td>0.28</td>
<td>0.02</td>
<td>0.69</td>
<td>–</td>
<td>–</td>
<td>–</td>
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<tr>
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<td>1.2</td>
<td>0.26</td>
<td>0.01</td>
<td>–</td>
<td>–</td>
<td>0.1</td>
<td>–</td>
<td>Post–MS</td>
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<td>1.4</td>
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<td>0.02</td>
<td>–</td>
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<td>–</td>
<td>Pre–MS</td>
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<tr>
<td>1.5</td>
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<td>0.02</td>
<td>0.01</td>
<td>–</td>
<td>–</td>
<td>0.15 Hp</td>
<td>TAMS</td>
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<tr>
<td>1.6</td>
<td>3.0</td>
<td>0.28</td>
<td>0.01</td>
<td>0.69</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>ZAMS</td>
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<tr>
<td>1.7</td>
<td>5.0</td>
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<td>0.02</td>
<td>0.35</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>MS</td>
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(selected in view of possible COROT targets)
## ESTA physics definitions

<table>
<thead>
<tr>
<th>ITEM</th>
<th>Selection</th>
<th>References</th>
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<tbody>
<tr>
<td>EoS</td>
<td>OPAL</td>
<td>Rogers et al. (1996, 2001 Tables)</td>
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<td>Reaction rates</td>
<td>NACRE</td>
<td>Angulo et al. (1999)</td>
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<td>Convection</td>
<td>MLT (α = 1.6)</td>
<td>Böhm–Vitense (1958) + Henyey et al. (1965)</td>
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<td>Overshoot</td>
<td>$\nabla = \nabla_{ad}$</td>
<td>Zahn (1991) + ...</td>
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<tr>
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<td>– none –</td>
<td></td>
</tr>
<tr>
<td>Mixture</td>
<td>solar</td>
<td>Grevesse &amp; Noels (1993)</td>
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<tr>
<td>Atmosphere</td>
<td>gray</td>
<td>–</td>
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</table>

(Additional details and clarifications in a separate ESTA-document)
0.9 $M_\odot$ – evolved MS model ($Z=0.02$)

(taken from Lebreton & Monteiro, ESTA meeting Nice, Sept. 2005)

<table>
<thead>
<tr>
<th>Case 1.1:</th>
<th>Age</th>
<th>$\frac{R}{R_\odot}$</th>
<th>$\frac{L}{L_\odot}$</th>
<th>$T_{\text{eff}}$</th>
<th>$\frac{T_c}{10^7}$</th>
<th>$\rho_c$</th>
<th>$X_c$</th>
<th>$\frac{M_{\text{cor}}}{M}$</th>
<th>$\frac{R_{\text{env}}}{R}$</th>
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<td>0.6245</td>
<td>5428</td>
<td>1.447</td>
<td>151.2</td>
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<td>0.6269</td>
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<td>1.452</td>
<td>152.3</td>
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<td>-</td>
<td>0.7002</td>
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<td>STAROX</td>
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<td>-</td>
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<td>TGEC</td>
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<td>5489</td>
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<td>-</td>
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<td>GARSTEC</td>
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<td>0.3500</td>
<td>-</td>
<td>0.6960</td>
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</tbody>
</table>
task 1.1 – chemical profile

- relative deviations generally below 0.5–1% except for Pisa code in centre, and Århus code around $^3\text{He}$ bump

dots: Garstec model
• definitely larger differences (age: 5% and more!)
• also in hydrogen profile (ZAMS–definition!) up to 10%
• problem: boundary of convective core
ESTA conclusions

- global quantities differences 1–5%
- age up to 20%
- convective core problem
- partially due to deviations from physics specifications or hidden differences
- pre-MS and overshooting increase differences
- CLES/CESAM₀ codes:
  - same origin (numerics)
  - very similar physics implementation
  - differences < 0.5%
Comparisons at low Z

- comparison of tracks for low-mass, low-metallicity stars
- differences in $Y_i$: 0.230 (Girardi, Yi) – 0.235 (VdB, Weiss)
- TO ages from 12.58 Gyr (Cassisi) to 13.74 (Weiss)
- 4 of 5 ages > 13.22 Gyr
The solar case

- same physics, but solar abundances
- all match solar constraints
- no diffusion in Girardi and VandenBerg
- $Y_i$ from 0.2670 (Yi) to 0.2768 (VandenBerg)
- $Z_i$ from 0.01810 (Yi) to 0.01998 (Weiss)
- $\alpha_{MLT}$ from 1.68 (Girardi) to 1.90 (VandenBerg)
standard 1 $M_\odot$ star ($Z=0.02$, $X=0.70$)

- blue: Weiss (Garstec)
- red: Salaris (FRANEC)
- green: Serenelli (LaPlata), analytical EoS
- black: Serenelli, Magni & Mazzitelli EoS
- Garstec: uncalibrated $\alpha_{\text{MLT}}$
- reaction rates and opacities similar
- grey atmospheres
- $T_{\text{eff}}$ differences on RGB up to 200 K!
standard 1 $M_\odot$ star ($Z=0.02$, $X=0.70$)

- blue: Weiss (Garstec)
- red: Salaris (FRANEC)
- black: Serenelli (LaPlata), analytical EoS
- Garstec: calibrated $\alpha_{\text{MLT}}$
- reaction rates and opacities similar
- grey atmospheres
- $T_{\text{eff}}$ differences on RGB below 100 K
systematic age difference between FRANEC (red) and Garstec (blue) ages due to MS evolution
0.9 $\text{M}_{\odot}$ $(Z=0.001, Y=0.250)$

- same physics as in solar mixture case
- HRDs agree much better

but ages differ more
(Serenelli model lives longer due to lower luminosity)
on-going comparisons

- RGB bump luminosity (from literature and calculations):

<table>
<thead>
<tr>
<th></th>
<th>Padova</th>
<th>Pisa</th>
<th>BASTI</th>
<th>Y²</th>
<th>Garching</th>
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</thead>
<tbody>
<tr>
<td>age (Gyr)</td>
<td>6.514</td>
<td>6.331</td>
<td>6.023</td>
<td>6.769</td>
<td>6.222</td>
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<td>log L/L_☉</td>
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<td>2.101</td>
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<tr>
<td>T eff</td>
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<td>3.689</td>
<td>3.694</td>
<td>3.689</td>
<td>3.693</td>
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<td>diffusion</td>
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<td>yes</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>overshooting</td>
<td>yes</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
</tr>
</tbody>
</table>

- RGB tip luminosity log L/L_☉ (1.0 M_☉, Z=0.001):
  - for timesteps “standard” → 0.01*standard
  - BASTI: 3.35 → 3.29
  - Garstec: 3.41 → 3.34 (saturation from 0.2*standard on )
Achim Weiß

**calibration attempts**

- define a set of simple problems
- and a standard set of input physics (ESTA is a good start)
- get stellar evolution modellers to present their solutions to these problems
- compare, learn, adjust ...
- independently, solve obvious discrepancies between 2 codes
  - bump brightness
  - RGB tip
  - RGB effective temperatures
  - MS lifetimes
suggested cases – to be discussed

- physics as defined by COROT/ESTA
- model exchange format: GONG
- ESTA cases, internal structure comparison
  - 1.1 (0.9 M⊙, X⊙ = 0.35, Z = 0.02)
  - 1.3 (1.2 M⊙, ZAMS, Z = 0.01)
  - 1.6 (3.0 M⊙, ZAMS, Z = 0.02)
- ZAMS cases (definition?), global quantities $L$, $T_e$, $p_c$, $T_c$
  - $X = 0.70$, $Y = 0.28$, $Z = 0.02$
  - $X = 0.749$, $Y = 0.25$, $Z = 0.001$
  - masses from 0.7 to 20 M⊙
- Evolution cases, global quantities $L(t)$, $T_e(t)$
  - $M = 1$ and 20 M⊙ (Z = 0.02), from ZAMS to tip RGB resp. end He–burning