Some inputs and developments of Cestam

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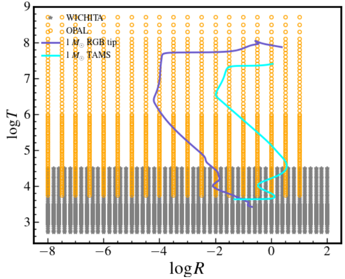
Opacity

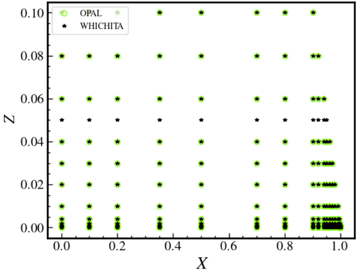
$$\frac{\partial T}{\partial m} = -\frac{GmT}{4\pi r^4 P}\nabla_{\rm rad,conv,cond}$$

$\Rightarrow$ radiation/conduction $\nabla = \frac{3}{16\pi acG}\boldsymbol{\kappa}\frac{P}{T^4}\frac{L}{m}$ with $\kappa^{-1} = \kappa_{rad,Ross}{}^{-1} + \kappa_{cond}{}^{-1}$

Several opacity table sets have to be patched

- *Envelope* : WICHITA (Ferguson et al. 04-...) include molecules and grains
- *Interior* :
  - → pre He-burning ($Z = Z_{\rm ini}$) : OPAL1 (Iglesias+ 96), OP (Seaton+92)





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  - → He-burning (C, O enhancements) OPAL2 (Iglesias+96, Boothroyd 07)
    Cestam: OPAL2 currently under test
- ⋆ *Conduction* (Cassisi, Pothekin+07)

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Preparation and implementation in Cestam

- ⋆ one single table covers all evolutionary stages (except He-burning)
- ⋆ interpolations/reasonable extrapolations on the same ($T, \log R, X, Z$) grid
- ⋆ smooth blend in overlapping regions
- ⋆ **pipeline in Fortran** for new table construction should be made available

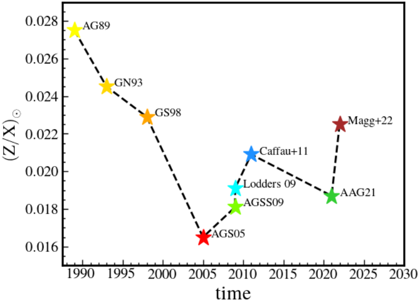
Solar mixture

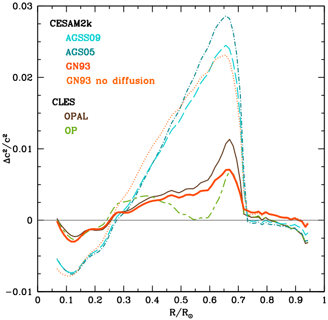
Any change requires new opacity tables

→ Inferred from theory, lab experiments, and observations

- ⋆ observations : solar photosphere, meteorites, ISM
- ⋆ 3D model atmospheres
- ⋆ up-dated atomic data

→ Individual abundances $Z_{i,\odot}$, global $(Z/X)_\odot$, isotopic ratios





Lebreton 2011

Opacity and solar mixture

Several sets of opacity tables available in Cestam

Mixture and tips used to get the OPAL-OP opacity tables

- Individual abundances: photospheric or meteoritic

  Either full photospheric

  or photospheric for volatile (C, N, O, Ne) and meteoritic for refractory (Mg, Si, S, Fe).

- Elements not explicitly taken into account by OPAL-OP

  Their abundances are shared by their nearest neighbors (by atomic number) in such a way as to conserve both number of particles and mean molecular weight (Iglesias+1991)

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Cestam: a bunch of opacity tables available

- ⋆ Presently used **Asplund, Amarsi, Grevesse (2021)**
- ⋆ Tables still used for comparison purposes

  Grevesse & Noels (93), **Grevesse & Sauval (98)**, Asplund+ (09)
- ⋆ Old outdated tables still available

  Anders & Grevesse (89), Asplund et al (05), α-elements Chaboyer (95)
- ⋆ To be prepared for PLATO? Magg et al. (2022)

Atmosphere: boundary conditions for the interior

Implementation of 1D convective model atmosphere grids

A set of grids

- ⋆ **ATLAS9** for **GS98** mixture (Kurucz 91, Castelli+02)

  $T_{\rm eff} \in [3500, 7000] K$; $\log g \in [1, 5]$, $[\rm Fe/H] \in [-1., +0.2]$; $[\alpha/\rm Fe] = 0.0$

- ⋆ **MARCS** for **Gustafsson+08** mixture

  $T_{\rm eff} \in [2800, 6500] K$; $\log g \in [-0.75, 6.0]$, $[\rm Fe/H] \in [-1., +0.5]$; $[\alpha/\rm Fe] \in [0.0, 0.4]$

- ⋆ **PHOENIX-BT-Settl** for **AGSS09** mixture (Allard+11)

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Method

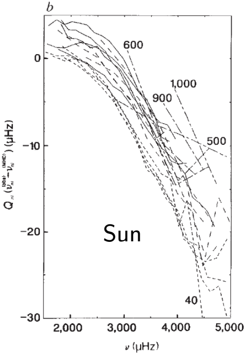
- ⋆ Extract $T(\tau)$-laws, density and pressure values from files
  game to play to find relevant information and build tables with no gaps.
- ⋆ Cestam: get $T(\tau), \rho_{\rm ext}$
  5 parameters interpolation: $T_{\rm eff}, \log g, [{\rm Fe/H}], [\alpha/{\rm Fe}], \tau$
  Currently under final validation

Atmosphere: near-surface effects for oscillation frequencies

1D stellar models plus adiabatic oscillation codes do not fit obs

$\nu_{\mathbf{mod}} > \nu_{\mathbf{obs}} \rightarrow$ **the higher the frequency, the higher the discrepancy.**

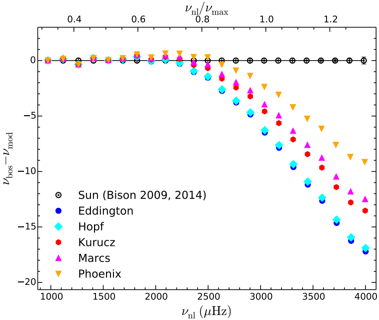
- ⋆ *Structural effects:* convection → P_{turb} rises upper layers → ν decreases
- ⋆ *Modal effects:* $\tau_{\mathrm{th}} \sim \Pi_{\mathrm{osc}}$ → non adiabaticity *(Sonoi, Belkacem, Dupret+17)*



Christensen-Dalsgaard, Däppen, Lebreton 88,

also Dziembowski 88

Different 1D atmospheric boundary conditions



Lebreton 2018

Evolved stages: He-burning phases through the He-flash

Internal structure equations

$\frac{\partial r}{\partial m} = -\frac{1}{4\pi r^2 \boldsymbol{\rho}}$ mass conservation

$\frac{\partial P}{\partial m} = -\frac{Gm}{4\pi r^4} + \frac{\boldsymbol{\Omega}^2}{6\pi r}$ hydrostatic equilibrium

$\frac{\partial L}{\partial m} = \boldsymbol{\epsilon}_{\mathbf{nuc}} - \boldsymbol{\epsilon}_{\boldsymbol{\nu}} - \frac{\partial U}{\partial t} + \frac{P}{\rho^2}\frac{\partial \rho}{\partial t}$ energy conservation

$\frac{\partial T}{\partial m} = -\frac{GmT}{4\pi r^4 P}\nabla$ with $\nabla = \boldsymbol{\nabla}_{\mathbf{rad}}, \nabla_{\rm conv}, \boldsymbol{\nabla}_{\mathbf{cond}}$ energy transport

Radiative transport $\nabla_{\rm rad} = \frac{3}{16\pi acG}\boldsymbol{\kappa}\frac{P}{T^4}\frac{L}{m}$

Evolution $\left(\frac{\partial X_i}{\partial t}\right) = \left(\frac{\partial X_i}{\partial t}\right)_{\rm nuc} + \left(\frac{\partial X_i}{\partial t}\right)_{\rm transport}$ with $\left(\frac{\partial X_i}{\partial t}\right)_{\rm nuc} = \rho A_i \sum_{\rm jk}\left(\boldsymbol{r^i_{jk}} - \boldsymbol{r^k_{ij}}\right)$

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Essential input physics

- ⋆ Extended nuclear reaction network for He-burning and beyond ✓
- ⋆ Neutrino losses (plasma ν and photoneutrinos) ✓
- ⋆ Mass loss : Reimers (75), Schröder & Cuntz (05), Blöcker (95) ✓
- ⋆ Conductive opacities (Cassisi et al. 2007) ✓
- ⋆ Opacity: C & O enhancements, He-burning (Iglesias+95) **under test**

Evolved stages: He-burning phases through the He-flash

Integration variables

- ⋆ Standard: optimal choice (to avoid singularities)
  $\xi{=}\ln P,\ \eta{=}\ln T,\ \mu{=}(M/M_\odot)^{\frac{2}{3}},\ \zeta{=}(R/R_\odot)^2,\ \boldsymbol{\lambda{=}\left(L/L_\odot\right)^{\frac{2}{3}}},\ \gamma{=}\ln\rho$
- ⋆ Change of variable for evolved stages ($L < 0$) ✓
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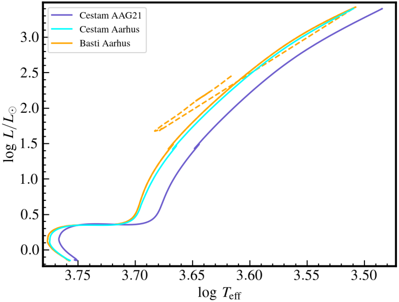
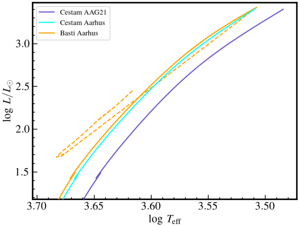
Choice of the mesh distribution (Eggleton 1971)

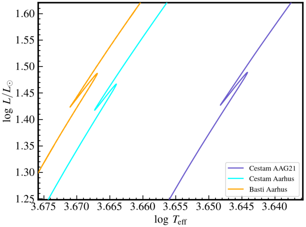
- Ensure variables $f^{(i)}$ do not vary by large amount from shell k to $k+1$
  → minimize $\sum_{k=2}^{N} \sum_i [f_k^{(i)} - f_{k-1}^{(i)}]^2$
  → variational problem $\delta \int_0^{M_\star} \sum_i (\frac{df^i}{dm})^2 \frac{dm}{dq} dm = 0$ with $q \in [0,1]$ and $q_{i+1} - q_i = C$
  → solution : $\frac{dq}{dm} = \phi \left\{ \sum_i (\frac{df^i}{dm})^2 \right\}^2$ and $\frac{d\phi}{dm} = 0$
- Practically in Cestam (based on P. Morel's experience)
  $f^{(1)} = c_P \ln P + c_T \ln T + c_M \mu + c_L \lambda$ and $f^{(i)=0, i \neq 1}$
  caution: requires that $f^{(1)}$ is **strictly monotonic**

Evolved stages: towards the He-flash

HR diagram

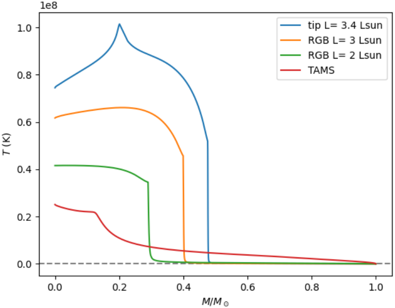


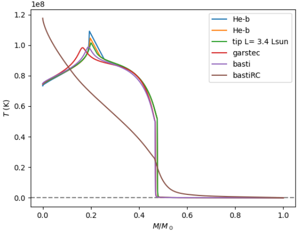


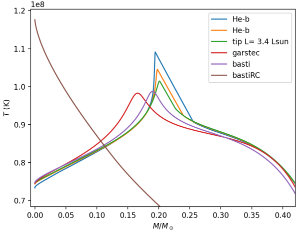


Evolved stages: towards the He-flash

Temperature profile evolution





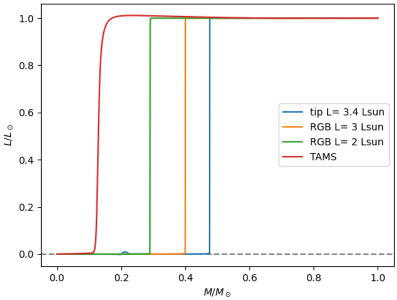


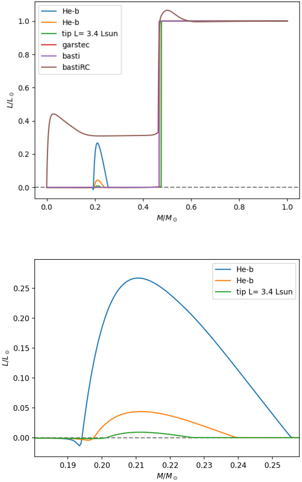
$$f^{(1)} = c_P \ln P + c_T \ln T + c_M \mu + c_L \lambda$$

can be non monotonic

Evolved stages: towards the He-flash

Luminosity profile





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Mesh adaption : work in progress!

Thank you for your attention