The Garching Stellar Evolution Code

Achim Weiss

Max-Planck-Institut für Astrophysik, Garching

Origin and history

- Kippenhahn, Weigert, Hofmeister (1967): THE CODE
- Thomas (1967 – late '70s): various versions, physics, numerics
- Weiss (early '80s – today): physics, modular structure
- Wagenhuber (1993 – 1997): numerical stability, modular structure
- Schlattl (1996 – 2005): physics, versatility

Programming language

- core in FORTRAN 77
- additions/changes since mid '90s in FROTRAN 90/95
- several "miscellaneous" (non-physical) routines in C
- ANSI-standard, fully portable
- pre-compiler features for package selection (EOS, opacities)

```
!   This is just a shortcut to inlcude the right EOS into the program
#ifdef mhd
#include "mhdeos.f"
#elif defined (opfine) || defined (opal) || defined (opal01)
#include "opaleos.F"
#else
#include "eos_inter.f"
#endif
```

Documentation

- "An Incomplete Guide to the Kippenhahn-Weigert-Hofmeister Stellar Evolution Code" (Weiss, 1988)
  - detailed description of routines
  - still valid for several routines
- "Documentation for Star2003" (Schlattl, 2004)
  - incomplete
  - documentation about code usage
  - including auxiliary programs and tools for output analysis
  - technical variables
  - source description missing
- Weiss & Schlattl (A&A Suppl. 144, 487, 2000)

Auxiliary routines and utilities

- suite of IDL-routines for data analysis and graphical display
- C-routines for handling of binary (model) data
- `make`-utilities (generation of `Makefile`)
- code available as complete package
  - source code
  - utilities source code
  - input data
  - starting model, parameter and abundance files
- `install+test` shell script: installation, compilation, sample run
- including adjustment to different OS-platforms (separate binary file trees)

Variables and equations

- Lagrange coordinate M_r/M (and alternatives)
- independent variables $\ln T$, $\ln P$, $\ln L_r/L$ (and alternatives)
- dependent variables $\ln \kappa$, $\ln \rho$ etc. also stored in model file
- four standard stellar evolution equations solved (spatial problem)
- optional: $v = \frac{\partial r}{\partial t}$ and $\frac{\partial^2 r}{t^2}$ term in pressure equation
- composition changes solved as temporal problem

Spatial and temporal problem

- solve spatial (boundary) problem at time t with composition $\vec{X}(t)$
- complete model from $M_r = 0$ to M in implicit scheme
- solve temporal (initial value) problem between models at time t and $t + \triangle t$
  - nuclear network
  - convective mixing (instantaneous or diffusive)
  - diffusion
  - or combinations up to burning and mixing solved simultaneously
  - spatial variables (T, ρ) kept constant over $\triangle t$
  - or predictor–corrector–method for estimating $T(t)$ etc.

Spatial resolution and grid control

- grid adjusted between two models at time t and $t + \triangle t$
- insertion and deletion of grid points; linear interpolation of quantities at inserted points
- grid resolution governed by curvature method (Wagenhuber & Weiss 1994)

  requirement: $\left| f(x_0 + \xi) - \left(f(x_0) + \frac{\mathrm{d}f(x)}{\mathrm{d}x}|_{x0}\xi \right) \right| < \delta$

  estimate: $\xi \approx (x_1 - x_0)\sqrt{\frac{\delta}{|3(f_1 - f_0) - (f_1' + 2f_0')(x_1 - x_0)|}}$

  check: $f(x_1) - \frac{\mathrm{d}f}{\mathrm{d}x}|_c(x_1 - x_0) < f(x_1)\delta$
- $\delta = 10^{-4} \cdots 10^{-3}$
- examples for grid point numbers: main sequence star: 600; red giant: 1000; helium flash: 2500; AGB: 1500–2500; SMM: 1900

Equation solver

- first-order Henyey block matrix solver for 4 equations
- generalized first order Henyey solver for arbitrary number of equations (for diffusion and burning–and–mixing)
- convergence monitoring with adjustable under-/overcorrection factors
- convergence criterion (typical): largest correction in variables anywhere $< 10^{-4}$
- set-back in case of divergence or slow convergence
- reduced accuracy in case of marginal convergence

Atmospheres

Various options:

- Eddington grey atmosphere
- Krishna-Swamy $t - \tau$-relation
- Lucy (1976) spherical atmosphere, including mass equation (AGB)
- always Rosselandt mean κ used!
- any outer boundary condition, e.g. from model atmospheres, fitted at $\tau = 1000$

Starting models

- usually "previous" model
- for ZAMS: total mass and composition adjusted for new problem without chemical evolution
- Runge-Kutta solver for models *from scratch* (PMS, ZAMS, HB)

Mass loss

- mass loss between two models
- Reimers formula, with variable η
- dust-driven winds (Wachter et al. 2002)
- technical procedure:
  - reduce total mass
  - keep number of grid points constant
  - keep T, P, r, L_r constant at grid points
  - rescale (stretch) mass at grid points down to some mass coordinate (parameter for affected depth)

Opacities

- opacity tables prepared outside stellar evolution program
- tables on X and Z grid
- program reads 3x7 tables or whole grid
- Alexander & Ferguson (1995) plus OPAL tables for *exactly same composition*
- for solar-scaled (Grevesse & Noels 1993 = "Seaton 1992") and α-enhanced metal mixtures (Weiss et al. 1994)
- combined, extended by Itoh (1992) electron conduction and Weiss, Keady, Magee (1989) opacities for $\lg T > 8.7$
- additional core tables for H-free mixtures
- large number of tables for additional mixtures (e.g. alternative α-element enhancement factors

Opacities/2

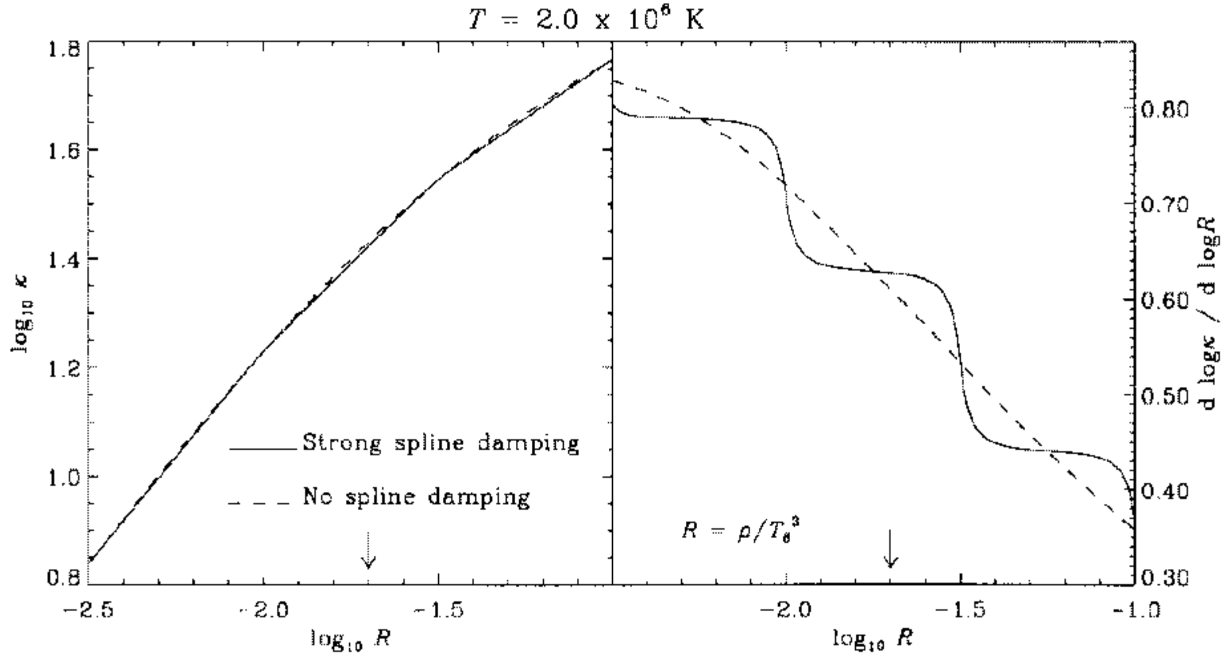
- linear interpolation in X and Z or $\log Z$
- bi-rational two-dimensional damped rational spline interpolation in T-R grid

$$f_k(x) = A_k u + B_k t + C_k \frac{u^3}{p_k t + 1} + D_k \frac{t^3}{q_k u + 1}$$

$$t = \frac{x - x_k}{x_{k+1} - x_k} \qquad u = 1 - t$$

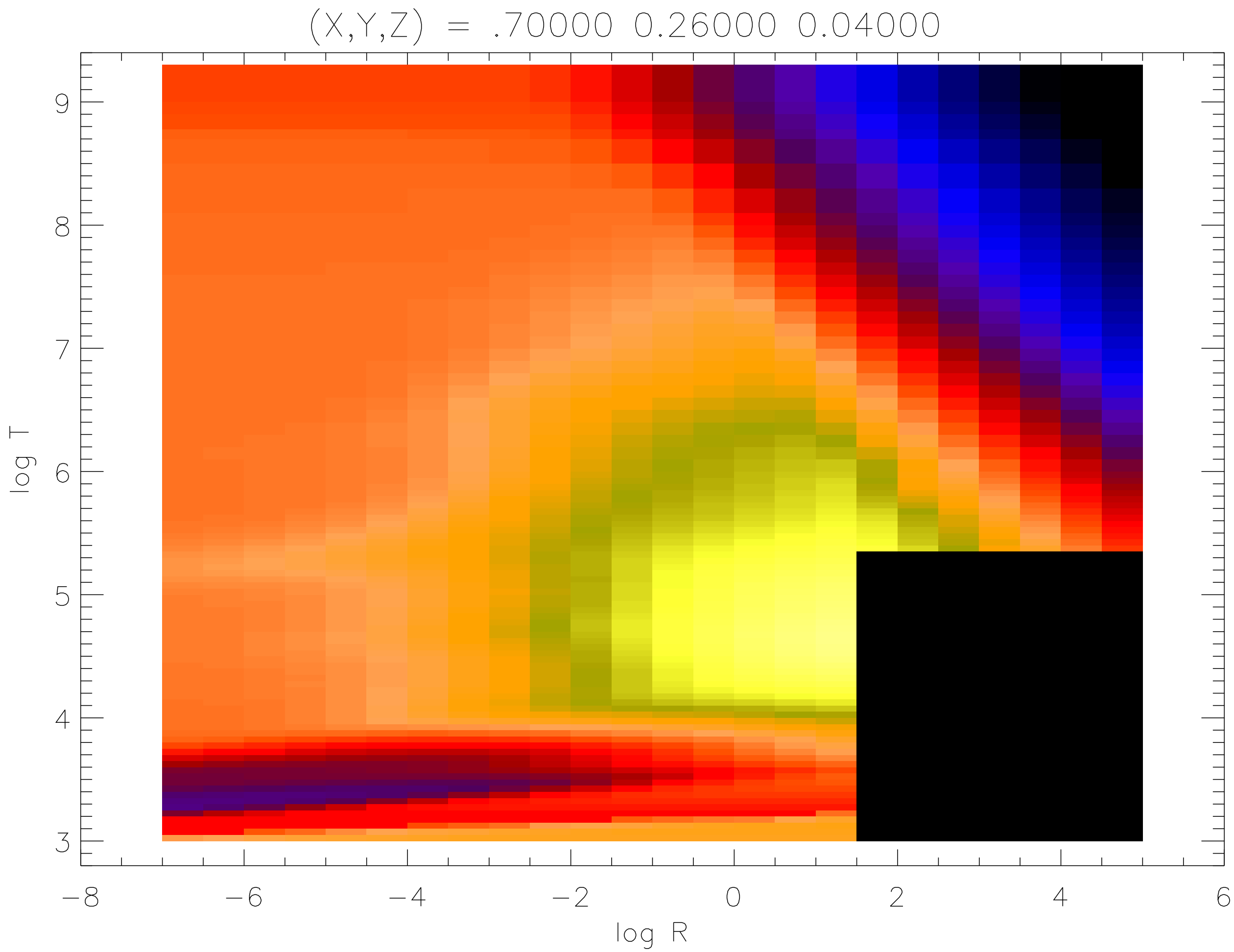
- contains adjustable parameter for cubic ($p = 0$) to linear ($p \to \infty$) interpolation
- one value of p for whole table

Opacity interpolation



experience shows, very slight damping best

Sample opacity table



non-rectangular tables possible (“ragged boundaries”)

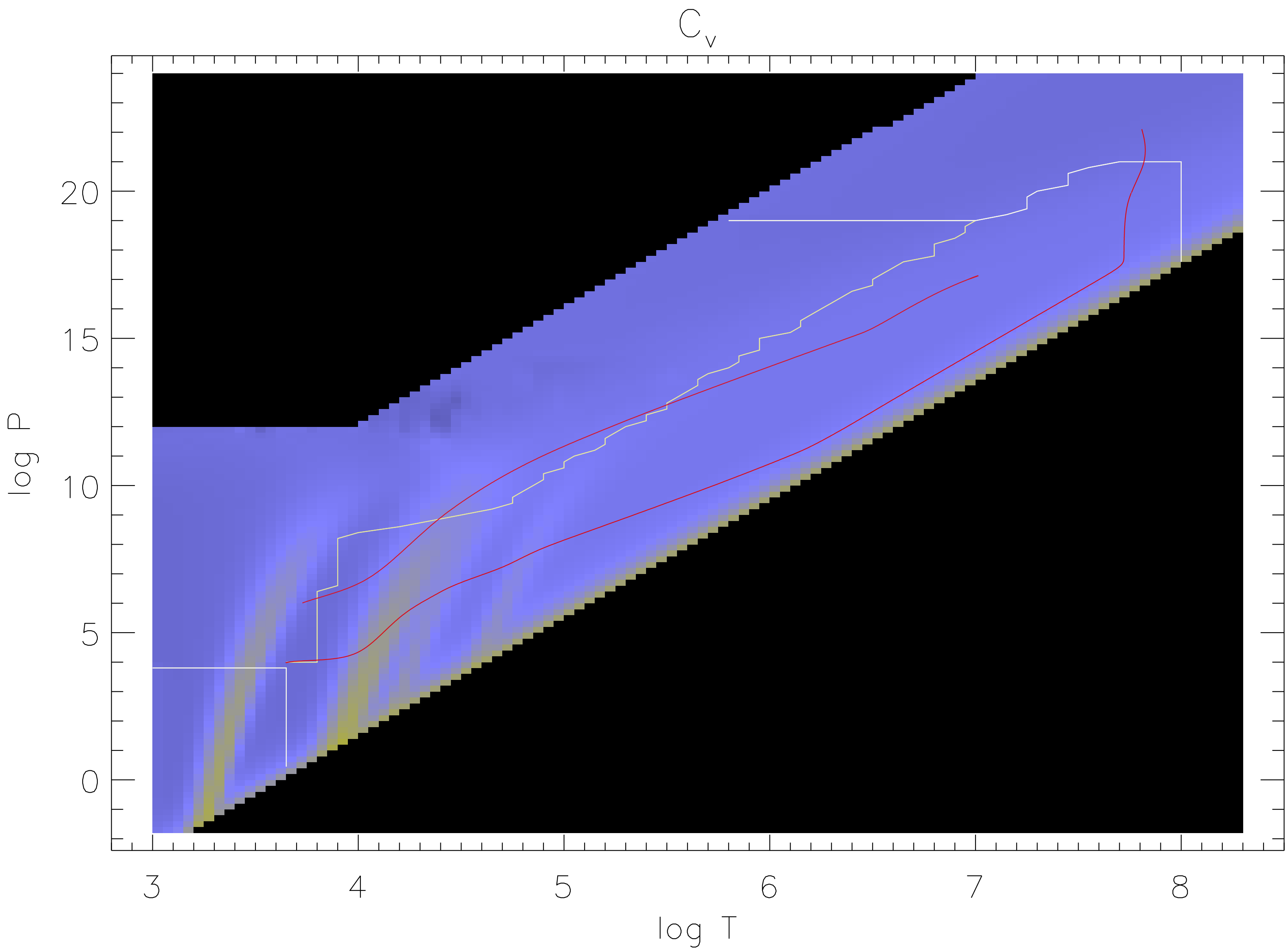
Equation of State

Choice of:

- Saha-EOS for H, He, C plus partially degenerate electron gas (analytic approximations by Thomas & Kippenhahn (1971), extended by Wagenhuber (1996))
- OPAL (Rogers et al. 1996); OPAL+ (2001) with OPAL interpolation routines; fine grid
- Mihalas et al. 1988 with OPAL interpolation scheme
- Irwin (2003) precalculated tables plus interpolation as for opacities
- SCOPE (Weiss 2001): tables from merging OPAL, Saumon+Chabrier, and EFF (Pols et al. 1995) with interpolation as for opacities

  SC only for H/He mixtures! Metals Z added to true Y

Sample SCOPE table



Convection

- Schwarzschild- or Ledoux-criterion
- convective, if $\nabla_{\rm ad} > \nabla_{\rm rad}$ for arithmetic mean over grid cell
- Mixing length theory; $\alpha_{MLT} = 1.6$ from SMM
- or Canuto/Mazzitelli (with $\alpha_{CM} = 0.9$)
- mixing instantaneous or as diffusive process (with $v_{\rm c}$ estimated from MLT)
- mixing over all convective grid cells, even if $\nabla_{\rm ad} < \nabla_{\rm rad}$ for last grid point
- overshooting as diffusive process a la Freytag et al. (1996)

$$D(z) = D_0 \exp \frac{-2z}{f H_P}$$

- semi-convection implemented, but not used

Non-Local, time-dependent convection

- theory by Kuhfuß (1987)
- implementation by Flaskamp (2003; PhD thesis)
- full three-equation model
- not (yet) suited for model calculations
- but for detailed comparison of theory with observations (seismic Sun, massive stars)

Diffusion

- diffusion coefficients calculated following Thoul et al. (1994)
- H/He-diffusion only
- or all elements, but with diffusive speed taken that of Fe
- no radiative levitation
- new: Paquette's integrals for diffusion constants plus quantum corrections (Schlattl 2004)

Energy production

- reaction rates: Coughlan & Fowler (1988), Adelberger et al. (1998), NACRE, and individual rates (e.g. Kunz et al. 2002 for $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$)
- outdated: equilibrium reaction rates for H- and He-burning
- standard: nuclear network for H-burning or "approximative" network (Woosley 1986) for He- and higher burning phases
  - H: pp-chains and CNO-cycles; β-decays instantaneously
  - for Li, Be, B: equilibrium assumed
  - optional: full p-capture nucleosynthesis (includes light elements and NeNa- and MgAl-cycle)
  - He: 3α, $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$, $^{16}\mathrm{O}(\alpha,\gamma)^{20}\mathrm{Ne}$
  - C- and higher: *very* rudimentary

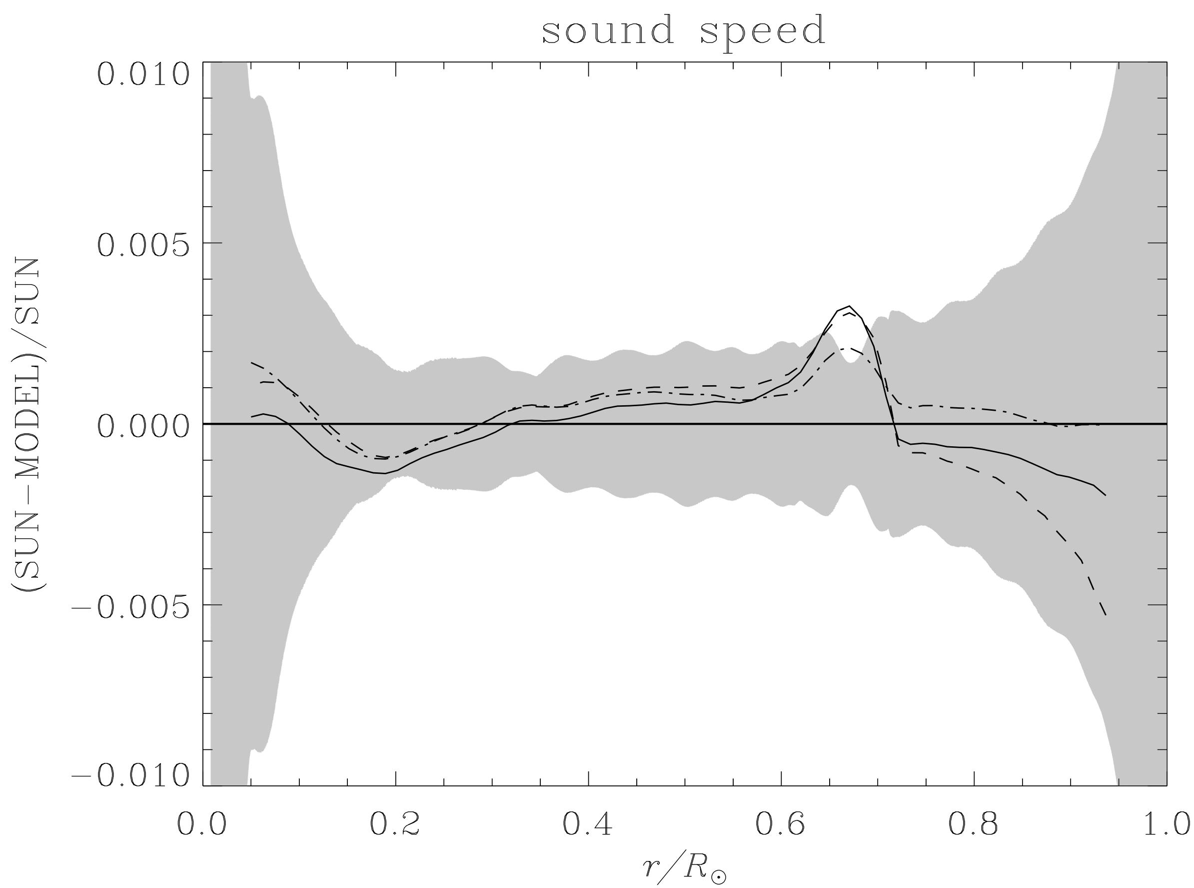
Energy production/2

- combined H- and He-network possible
- energy generation calculated from full network solution $\rightarrow \triangle Y_i$ and binding energies
- electron screening: Salpeter (1951)
- mass deficit due to nuclear energy production considered
- plasma neutrino losses: Munakata et al. (1988) and Haft et al. (1994) for plasma neutrinos
- thermal energies: $-T\frac{\partial s}{\partial t}$ approximative as in Kippenhahn & Weigert (1990) or including *mixing entropy* terms ($\mu_i \frac{\partial n_i}{\partial t}$)
- $-T\frac{\partial s}{\partial t}$: standard first order; recently second order expression (Lucy 2005)

Chemical evolution

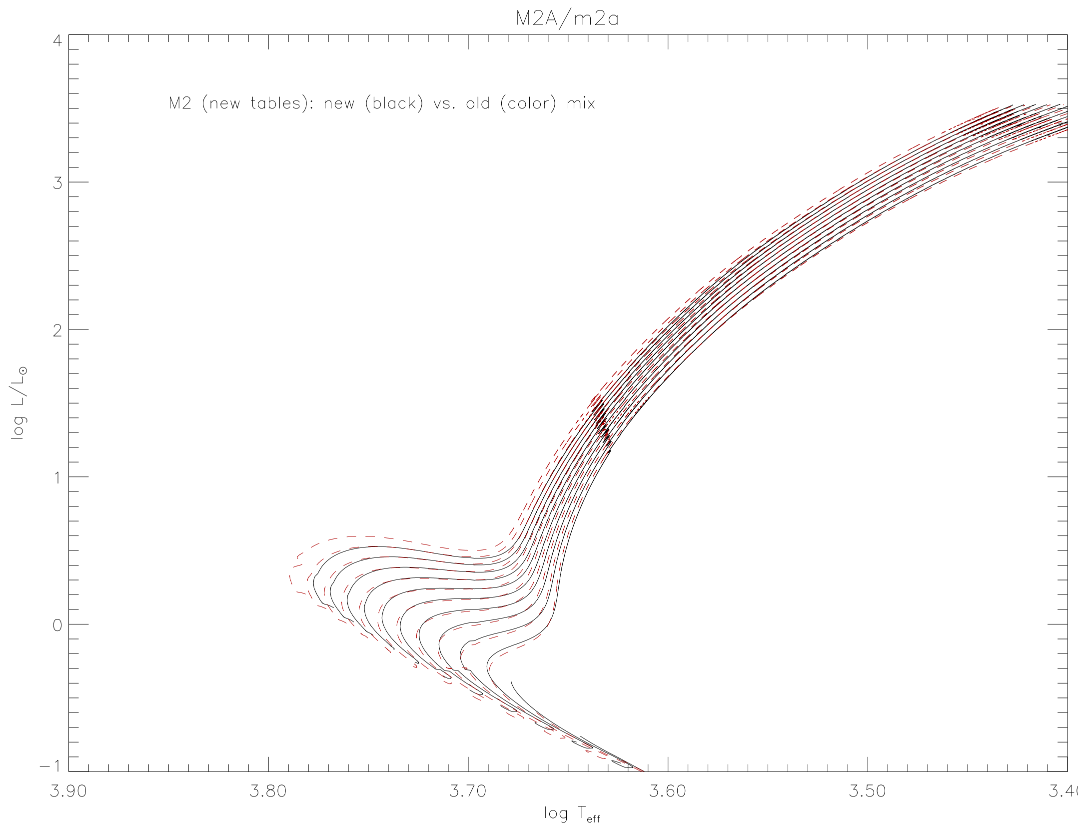
- between two models for time t and $t + \triangle t$
- solved with same network as for energy generation
- network: implicit backward differencing scheme
- linearized, solutions for $\triangle Y_i$
- "nuclear" timestep $1/100$ of evolutionary $\triangle t$, but adjustable
- max. number of timesteps or until $\triangle t$ is reached

Examples: the solar model



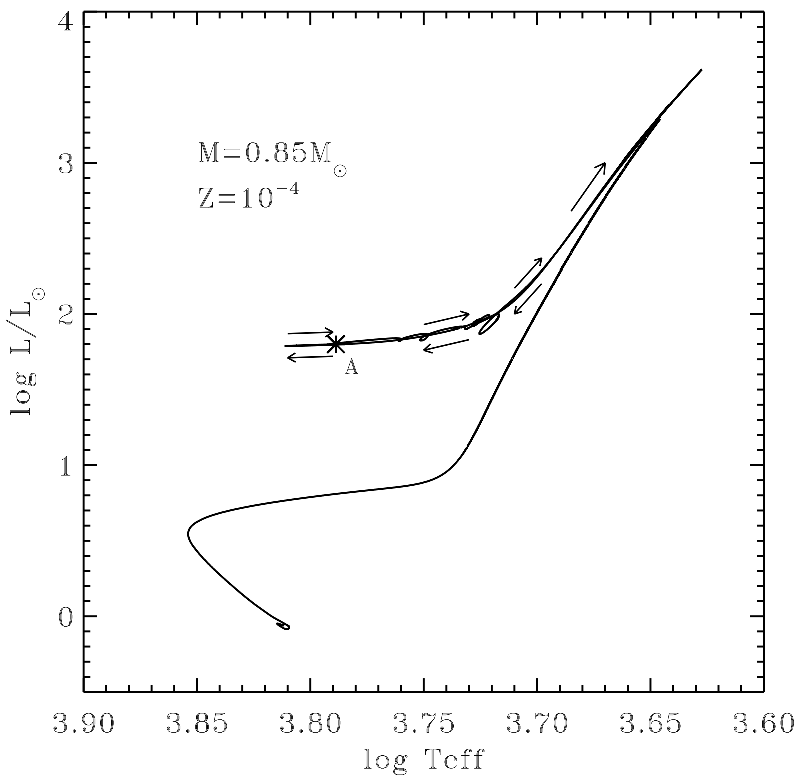
Grevesse & Sauval composition; with diffusion; in comparison to model S of Christensen-Dalsgaard and Bahcall & Pinsonneault 1995 (Schlattl & Weiss 2001)

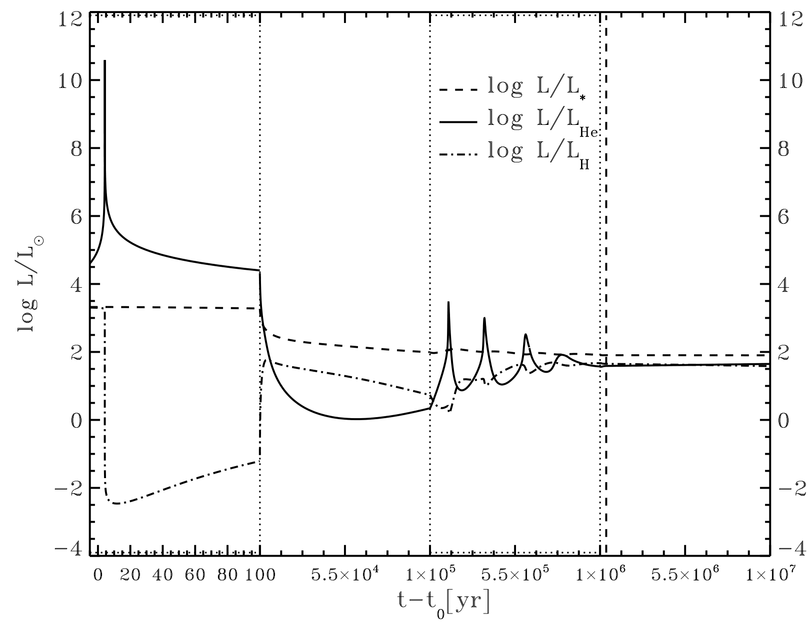
Examples: grids of low-mass stars



α-enhanced mixtures: effect of relative element abundances; new Ferguson (2005) tables; $M/M_\odot = 0.6 \cdots 1.3$ (Weiss, Ferguson, Salaris 2005)

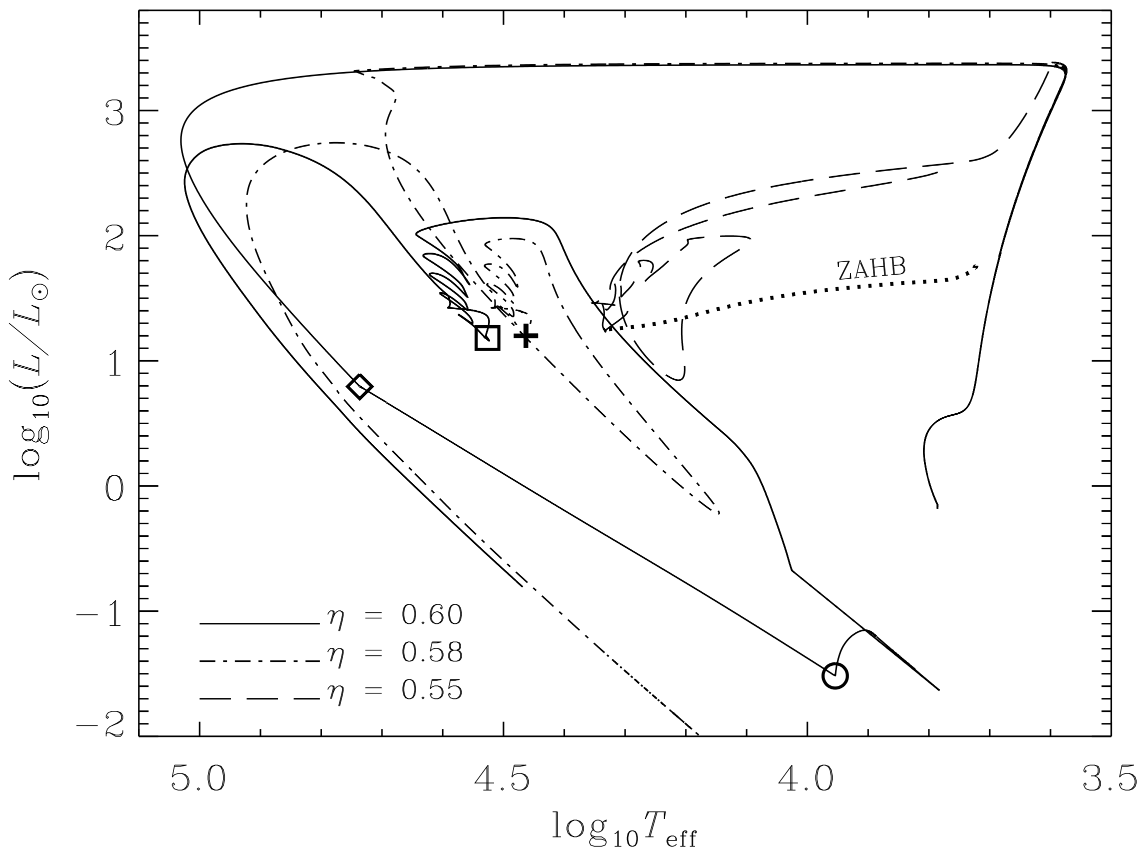
Examples: ZAHB models





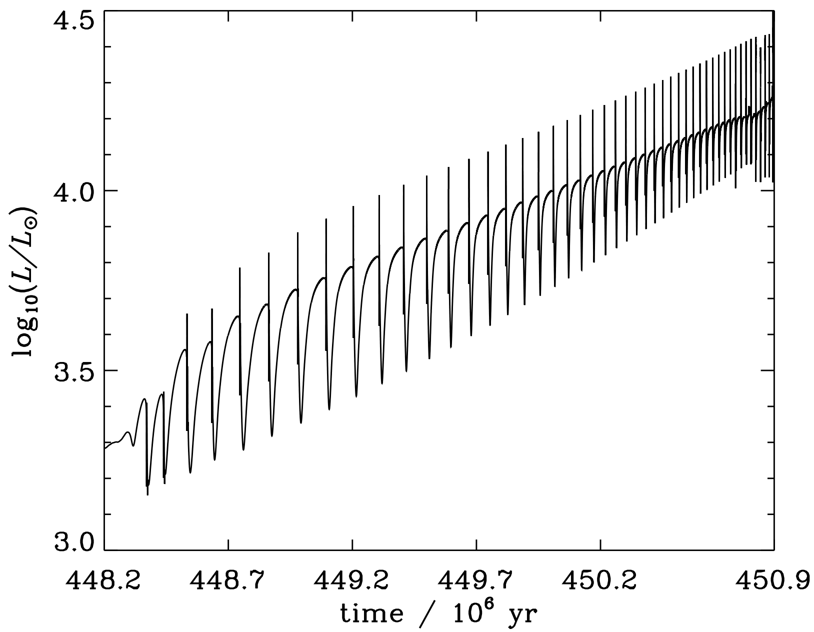
Calculations through core helium flash in $0.85\,M_\odot$, $Z = 0.0001$ star (Serenelli & Weiss 2005)

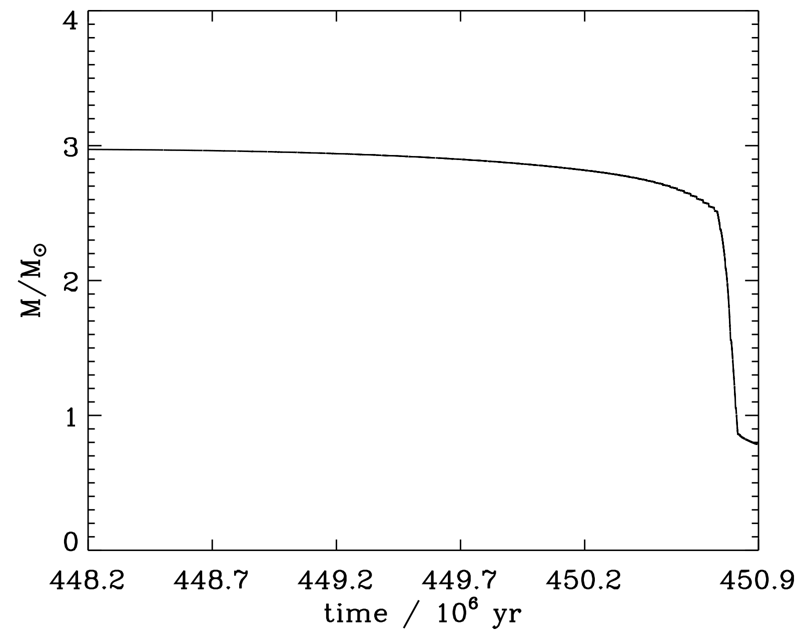
Examples: core helium flash with p-mixing



Late core helium flash in low-mass Pop. II star including mixing between H-rich envelopes and He-burning layers (Cassisi, Schlattl, Salaris, Weiss 2003)

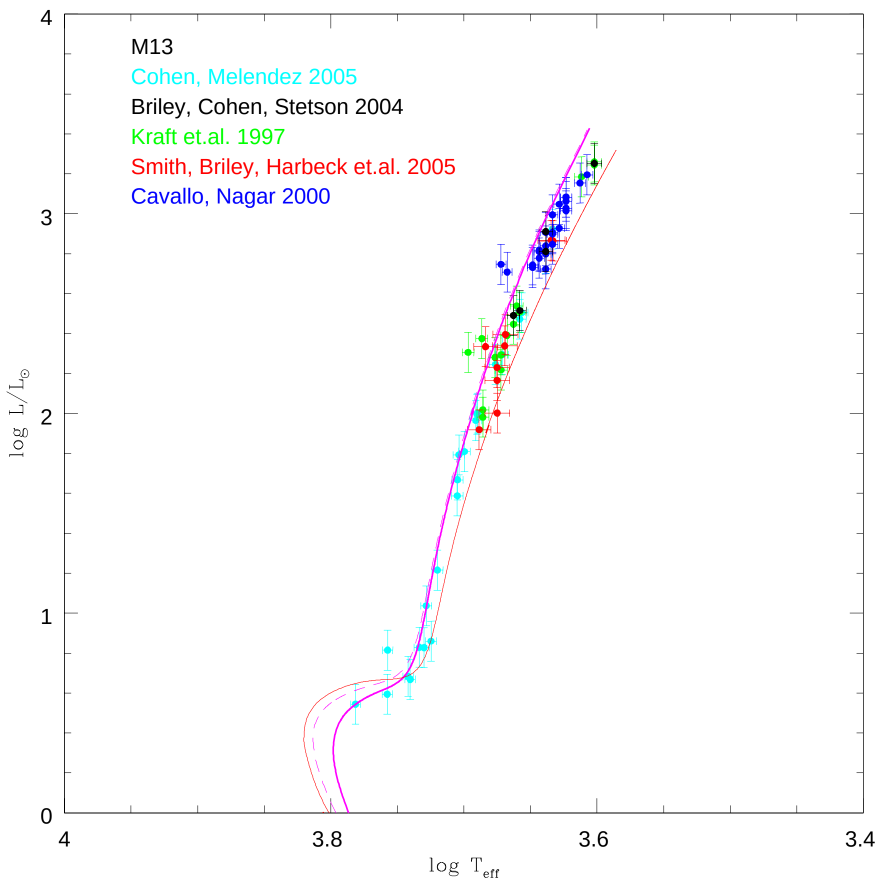
Examples: AGB evolution





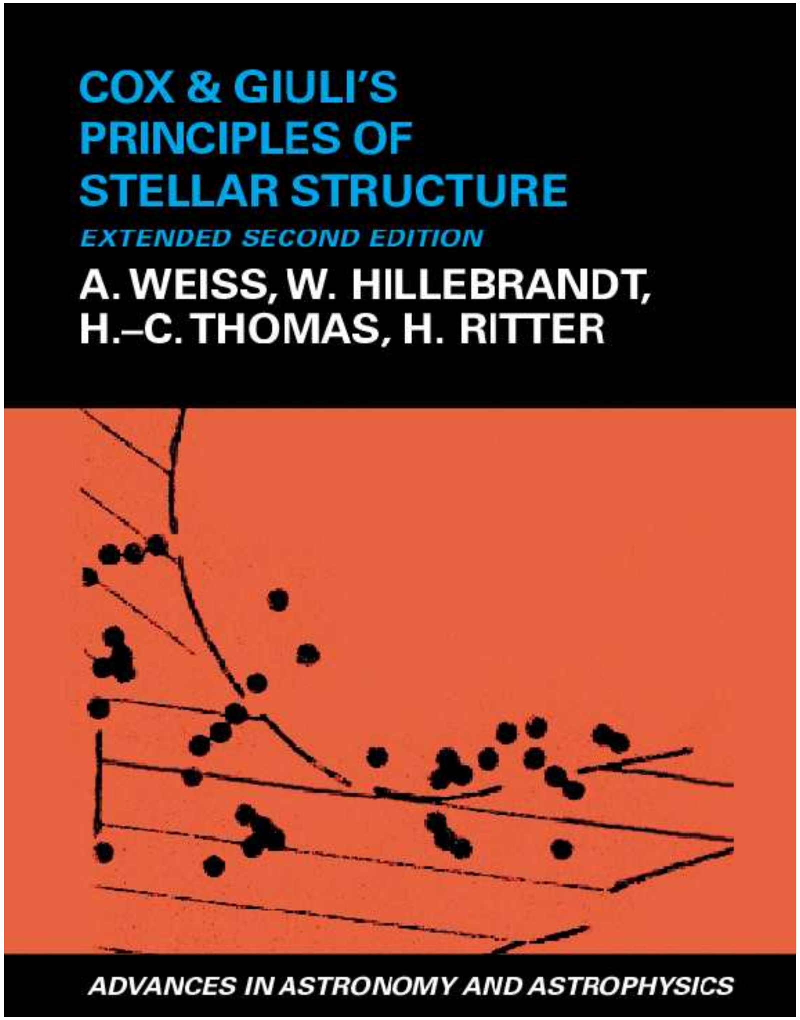
Luminosity and total mass during AGB-phase of a $3\,M_\odot$ star with $Z = Z_\odot$, with dust-driven mass loss (Kitsikis & Weiss 2005)

Examples: model calibration



Comparison of model $T_{\rm eff}$ and spectroscopic data for globular cluster M13, [M/H]=-1.3 (Gieseler & Weiss 2005). The magenta lines are isochrones with (solid) and without (dashed) diffusion, the red line an $0.9\,M_\odot$ evolutionary track with $\alpha_{\rm MLT} = 1.5$.

back in print:



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