Stellar microphysics

Atomic diffusion, accretion, thermohaline convection, links with asteroseismology

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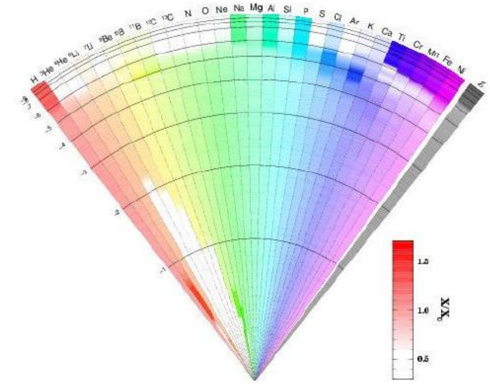
Waves and Physics, for Douglas' birthday, june 2011

Element Diffusion in Stars



Basics of stellar physics : two kinds of processes in competition

- « microscopic processes » (atomic diffusion)
- « macroscopic processes » (mixing, mass loss, accretion)

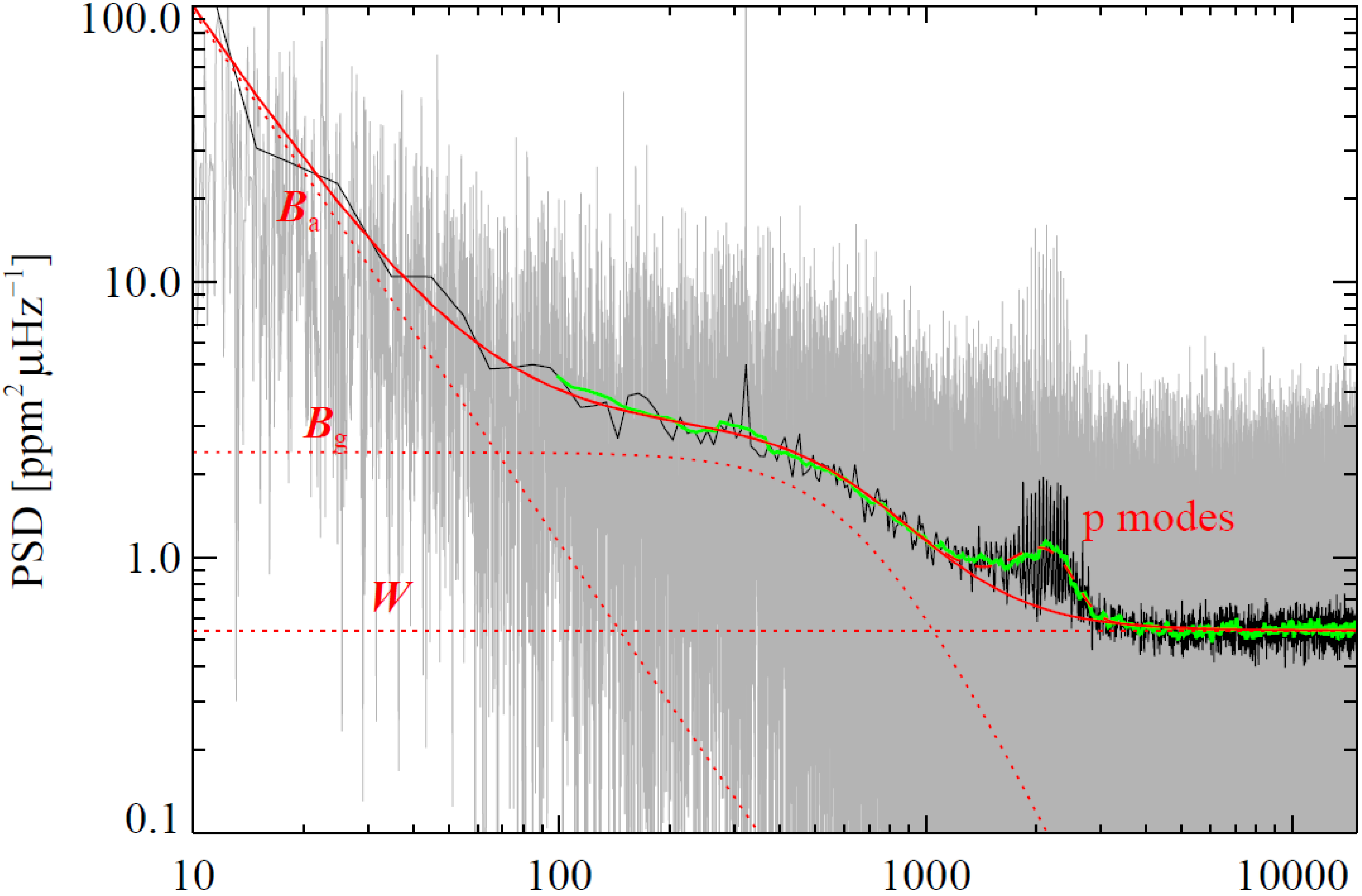
Importance of precise microphysics for stellar structure and evolution

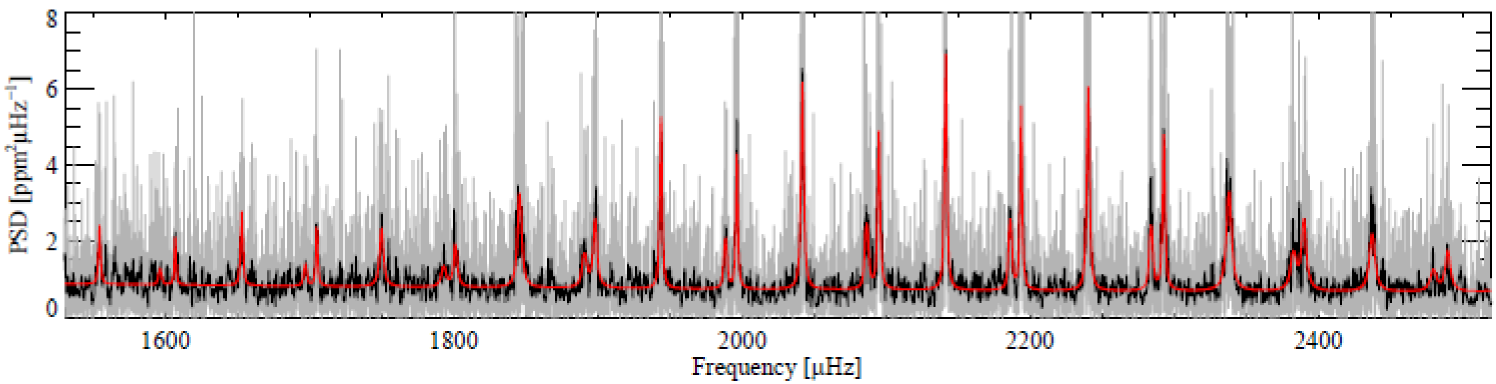
1) gravitational settling (many codes)
2) thermal diffusion (not as precise)
3) concentration gradients (mostly important in case of mac motions)
4) radiative accelerations (Montreal, Yale, Toulouse)

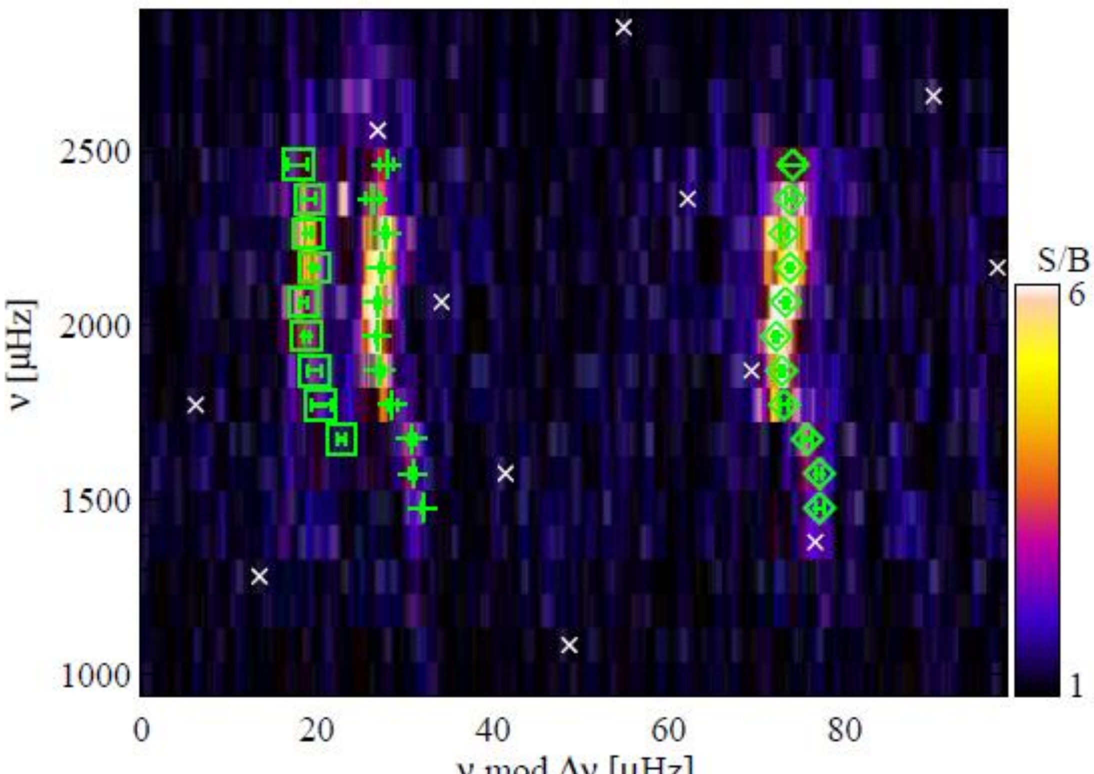
-Large data basis on atomic physics, in relation with opacity projects:
OPAL , OP…

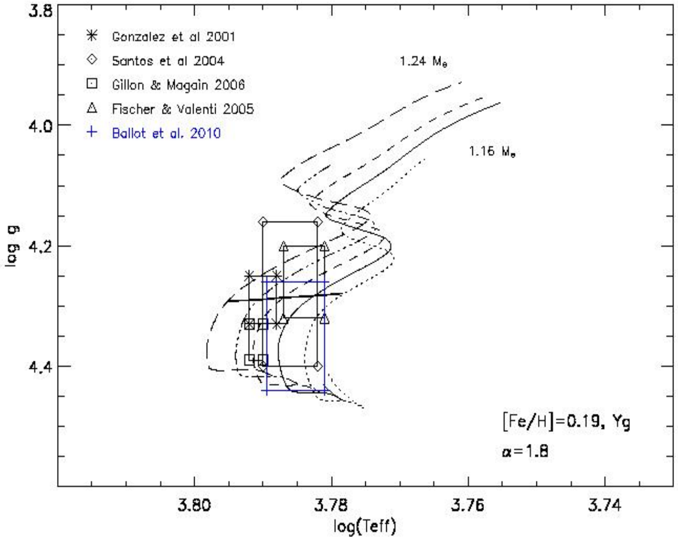
-Helio and asteroseismic tests
e.g. helium gradients below convective zones and many other consequences

HD 52265



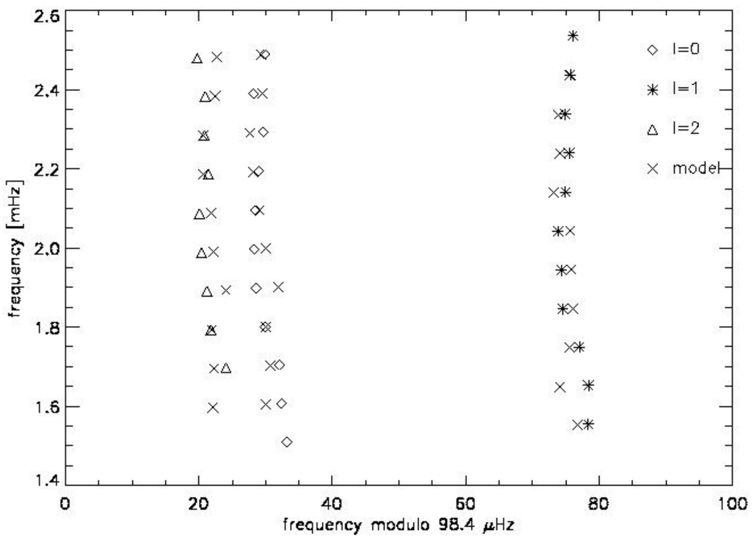

PSD [ppm²μHz⁻¹]
Frequency [μHz]
0
2
4
6
8
1600
1800
2000
2200
2400


ν [μHz]
ν mod Δν [μHz]
S/B
6
1
1000
1500
2000
2500
0
20
40
60
80

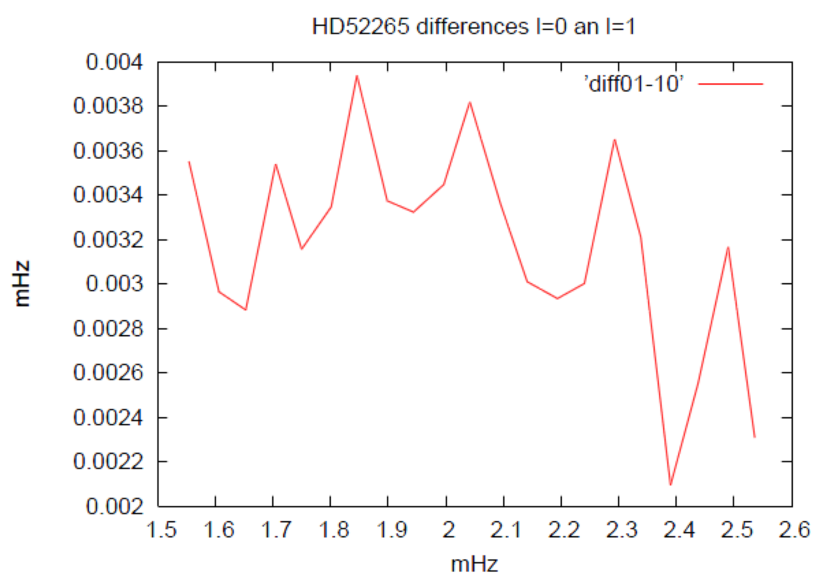


[Fe/H]	Y	α	Mass	Age [Gyr]	$\log g$	T_{eff}	$L/L_\odot$	$R/R_\odot$	M/R^3	$\Delta\nu$	$\delta\nu_{02}$
0.19	0.2878	1.8	1.18	3.373	4.283	6063.73	2.051	1.296	0.54	98.35	7.57
0.19	0.2714	1.8	1.22	3.194	4.288	6072.67	2.109	1.310	0.54	98.33	7.75
0.23	0.2929	1.8	1.20	2.949	4.286	6092.98	2.111	1.302	0.54	98.44	7.95
0.23	0.2714	1.8	1.24	3.014	4.290	6062.33	2.118	1.317	0.54	98.42	7.86
0.19	0.2878	1.4	1.25	1.055	4.290	6114.88	2.183	1.314	0.55	98.38	9.81

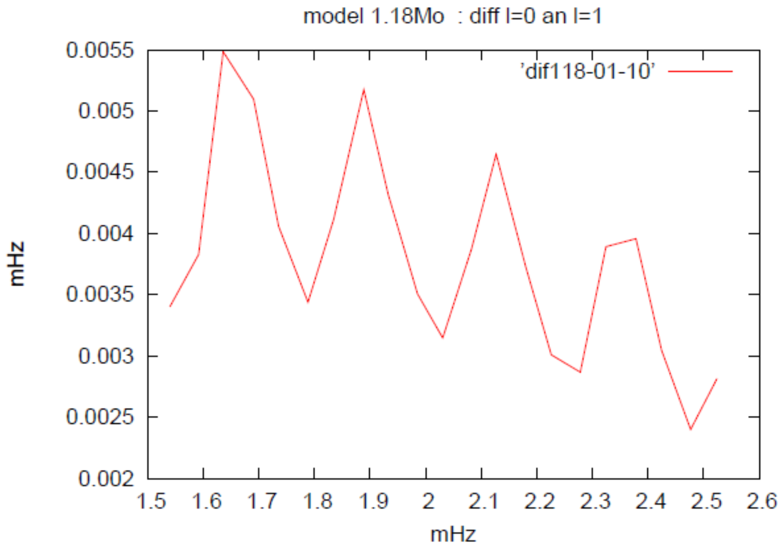
Some models obtained with the TGEC

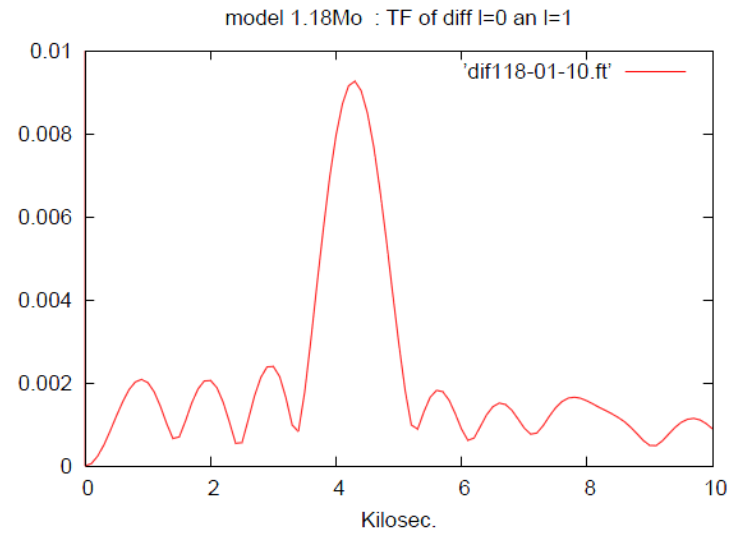


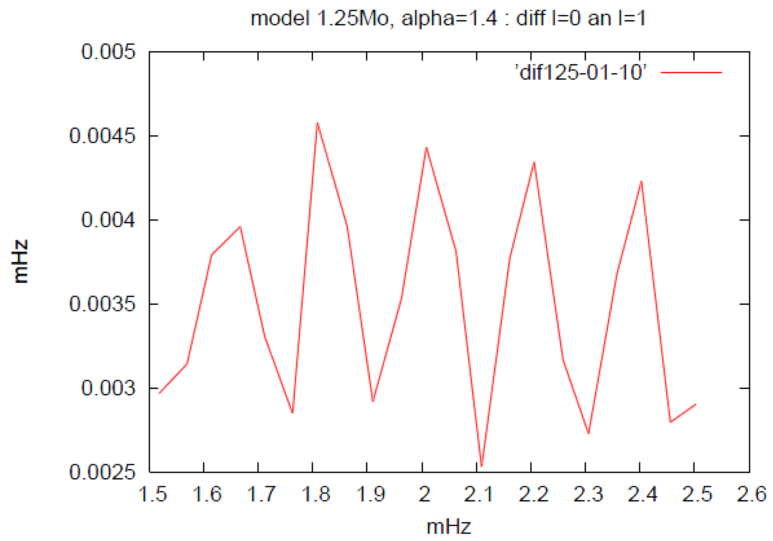
Observations: δ_{01}

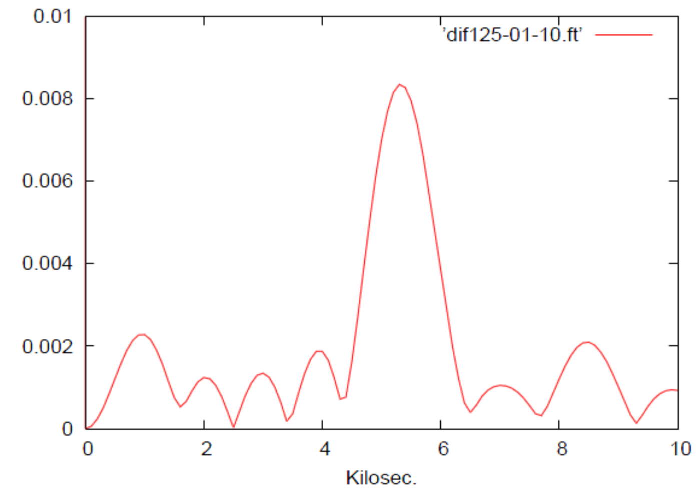


Models: δ_{01}

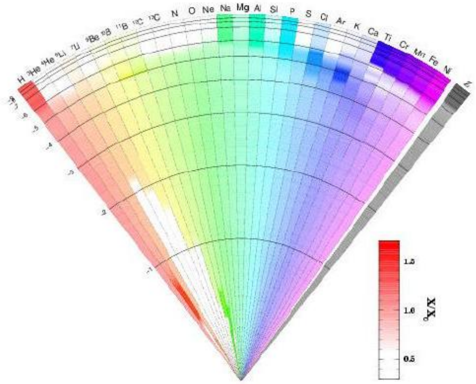








Some approximate expressions



Diffusion velocities:

$$v_d = -D\left[\frac{1}{c}\frac{\partial c}{\partial r} - \frac{m(g_R - g_{GT})}{kT}\right]$$

with:

$$D = \tfrac{1}{3} l C_M = \tfrac{1}{3} t_{col} {C_M}^2 = t_{col}\frac{kT}{m}$$

$$\longrightarrow\ v_d \sim t_{col}\, g_{eff}$$

Diffusion time scales:

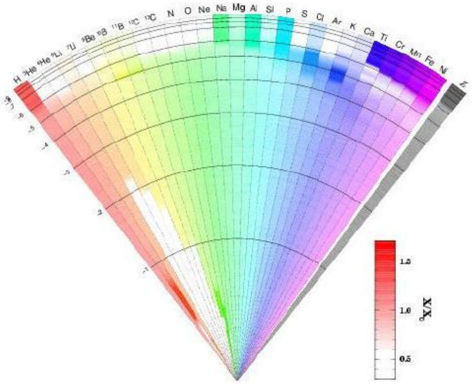
$$t_d \sim h(r)/v_d$$

Radiative accelerations:

$$F(A)\,dv = \frac{K_\nu(A)}{X(A)}\frac{\phi_\nu\, dv}{c}(\mathrm{cm\,s^{-2}})$$

with:

$$K_\nu(A) = \frac{1}{\varrho}\sum_{i,n} N_{i,n}\,\sigma_{i,n}\,(\mathrm{cm^2\,g^{-1}})$$

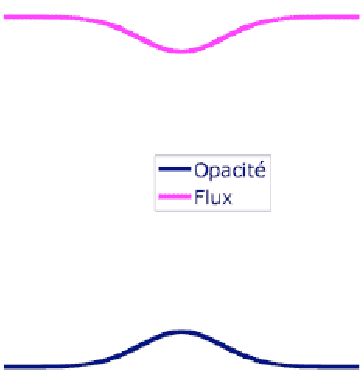


Radiative accelerations (cont'd):

$$g_{\rm rad}(A) = \frac{1}{4\pi r^2}\frac{L_r^{\rm rad}}{c}\frac{\kappa_R}{X_A}\int_0^\infty \frac{\kappa_u(A)}{\kappa_u(total)}\mathcal{P}(u)du$$

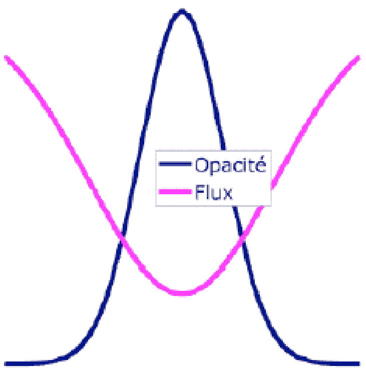
$$\mathcal{P}(u) \equiv \frac{15}{4\pi^4}\frac{u^4 e^u}{(e^u-1)^2} \qquad\qquad u \equiv h\nu/kT$$

unsaturated line



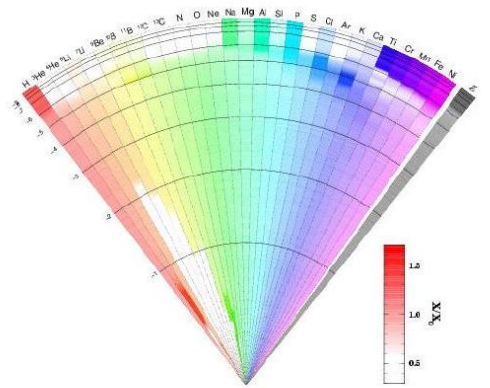
g_{rad} independent of N

saturated line



g_{rad} ↑ when N↓

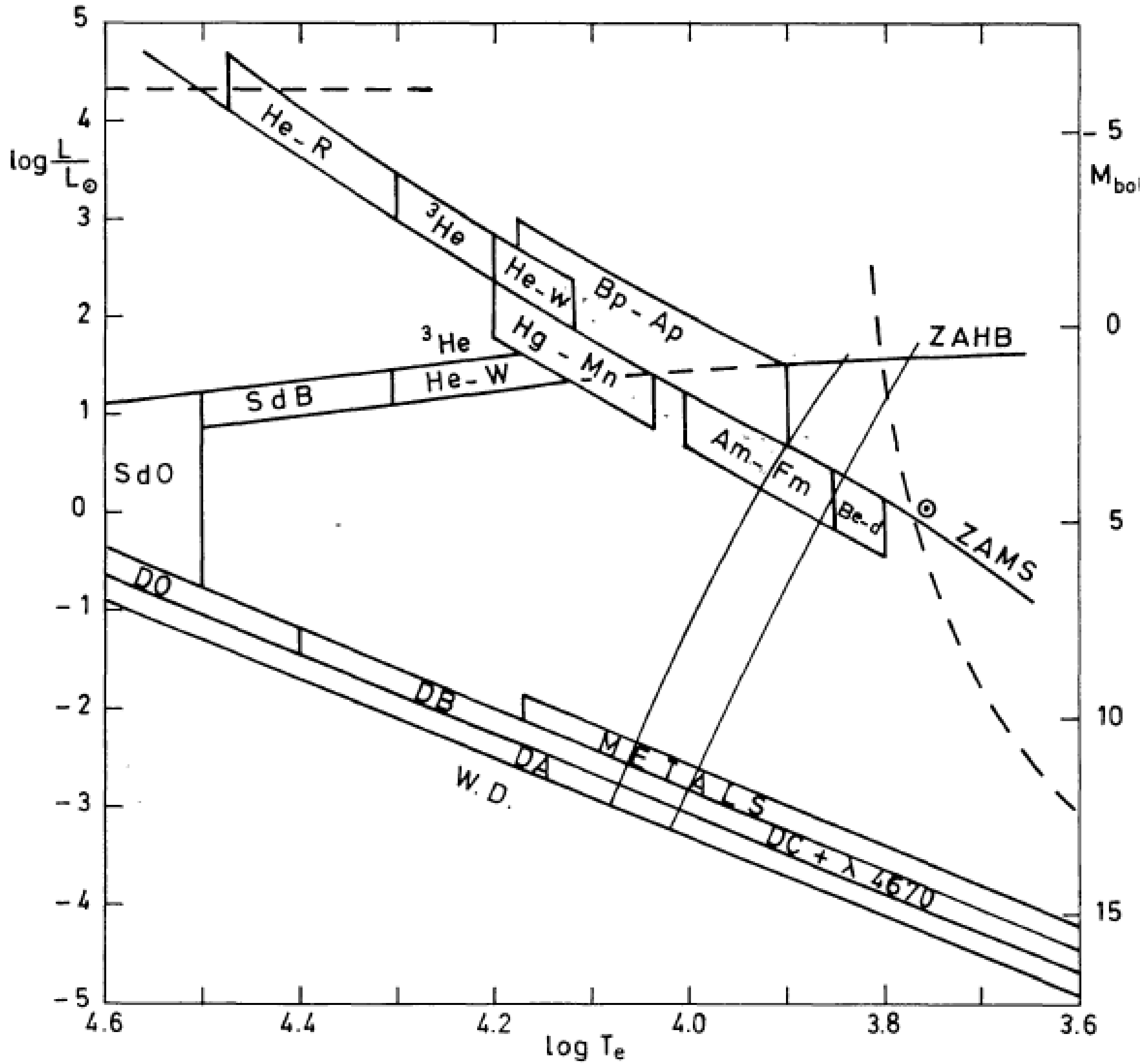
Orders of magnitude



- Atomic diffusion is a very slow but efficient process
- V_d increases and t_d decreases towards the surface
- Below the solar convective zone: $t_d \sim 10^{10}$ yrs
- In atmospheres: $t_d \sim 10^2 \sim 10^4$ yrs
- At the bottom of the second convective zone in Am stars:
  $D_m \sim 100$ cm^2/sec , $t_d \sim 10^6$ yr, $v_d \sim 10^{-6}$ cm/sec, $t_{col} \sim 10^{-10}$ sec
- Competition with macroscopic motions : selective vs homogenizing processes

$$v_d = -D\left[\frac{D+D_M}{D} \frac{1}{c}\frac{\partial c}{\partial r} - \frac{m(g_R - g_{GT})}{kT} \right]$$

1982



He_R
3He
He-w
Bp - Ap
Hg - Mn
He- W
SdB
SdO
ZAHB
Am-Fm
Be-d
ZAMS
DO
DB
DA
W. D.
METALS
DC + λ 4670
log L/L⊙
Mbol
log Te

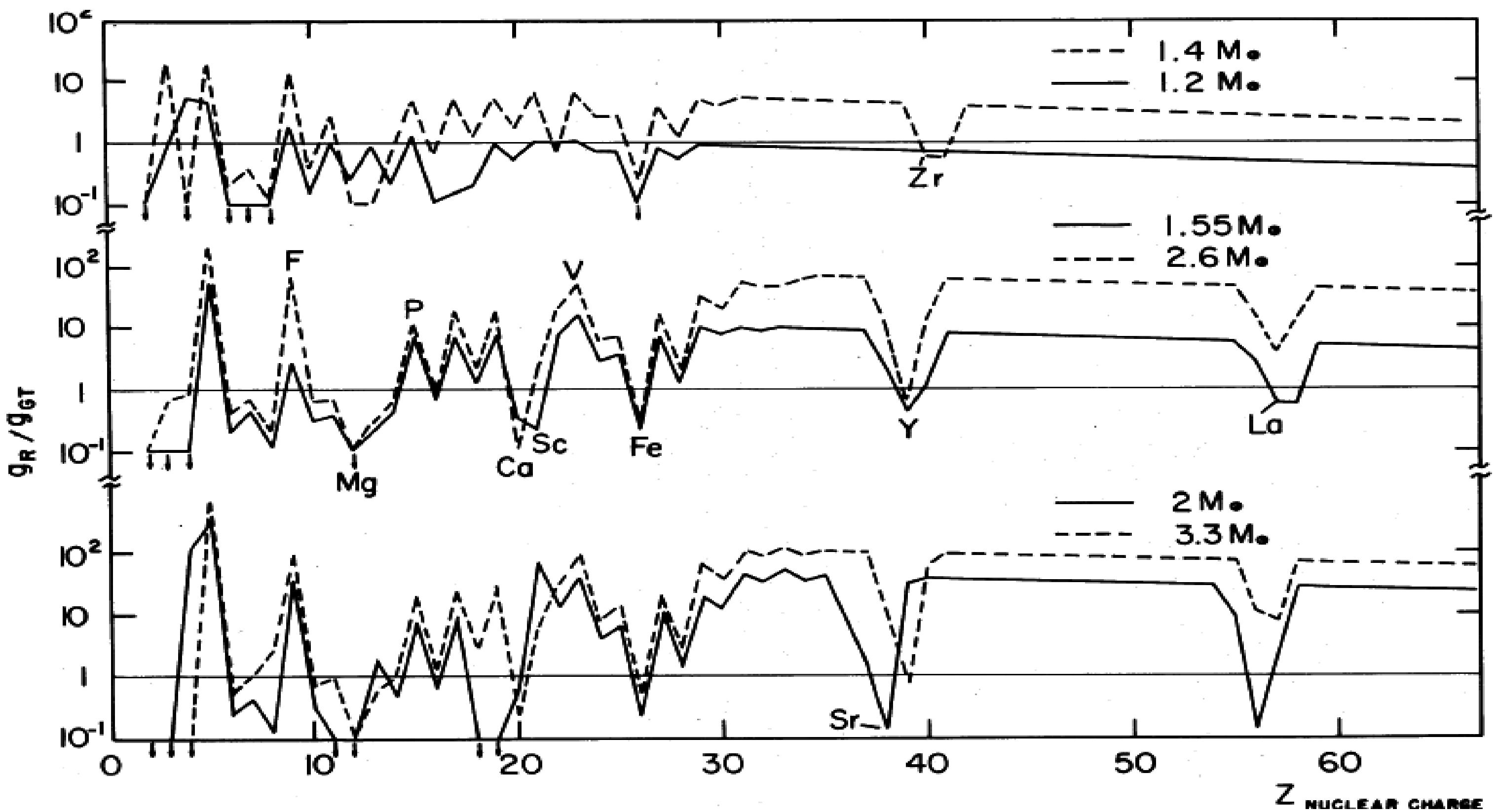
THE ASTROPHYSICAL JOURNAL, 210:447–465, 1976 December 1

DIFFUSION IN MAIN-SEQUENCE STARS: RADIATION FORCES, TIME SCALES, ANOMALIES

GEORGES MICHAUD * AND YVES CHARLAND
Département de Physique, Université de Montréal

AND

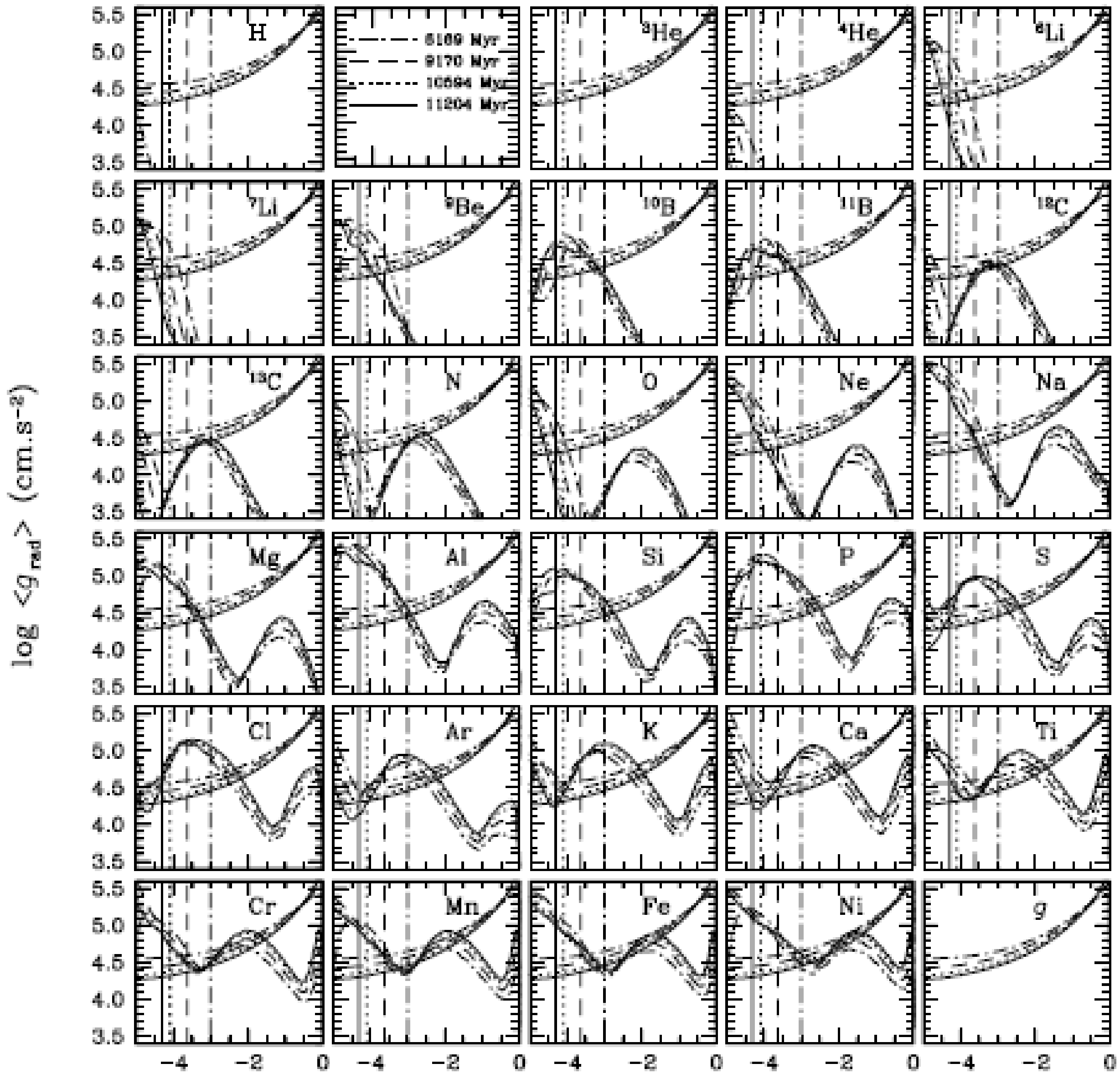
SYLVIE VAUCLAIR AND GÉRARD VAUCLAIR
D.A.F. Observatoire de Meudon
Received 1976 March 8

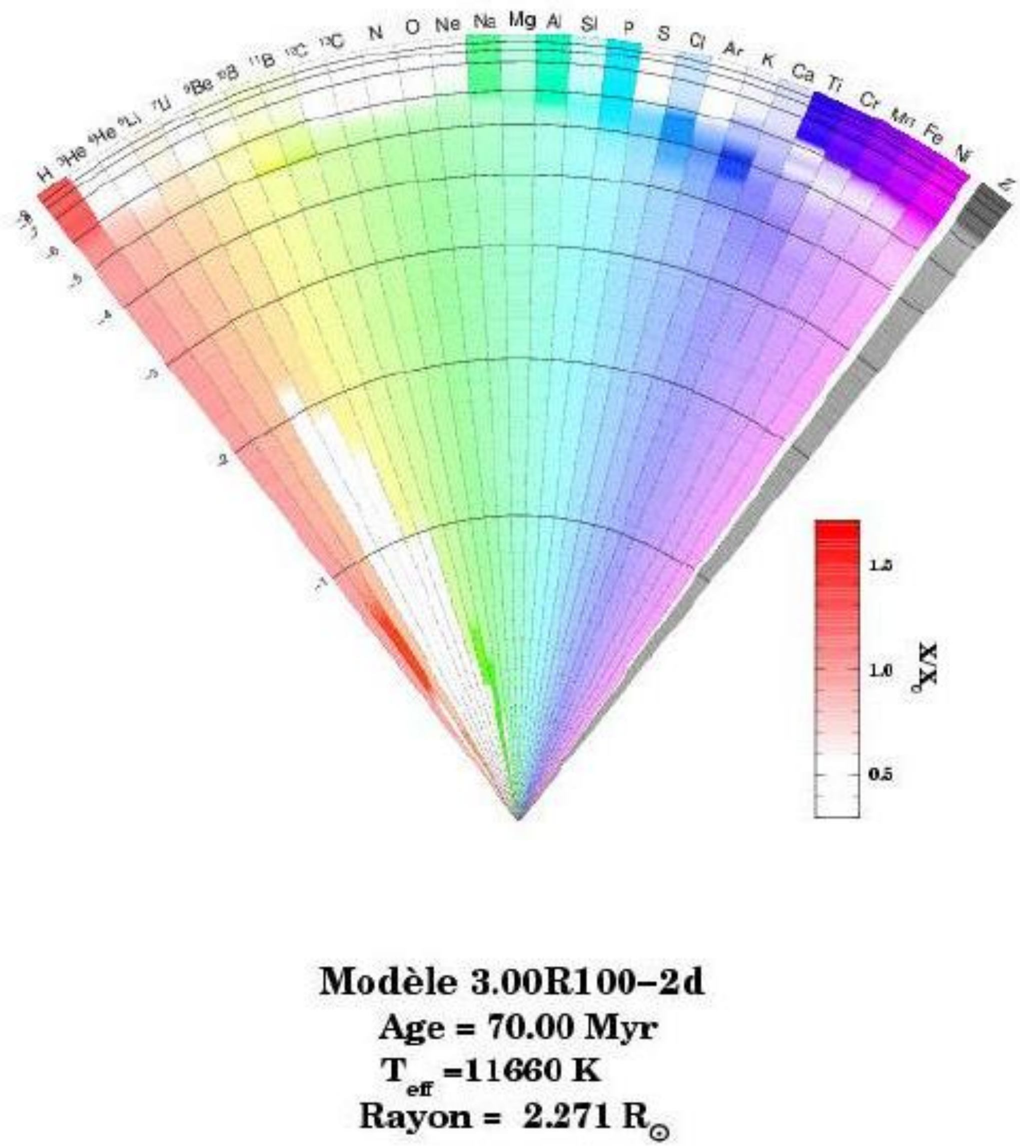


Radiative accelerations, full method

Richard , Michaud, Richer et al 2002
Ap.J. 568, 979
Using OPAL

See also:
Théado, Vauclair, Alecian, Leblanc,
ApJ 704, 1262, 2010
using SVP and OP





Examples of color intensity coded elements concentrations after pure diffusion
Richier, Richard, Michaud

Iron convective zones :

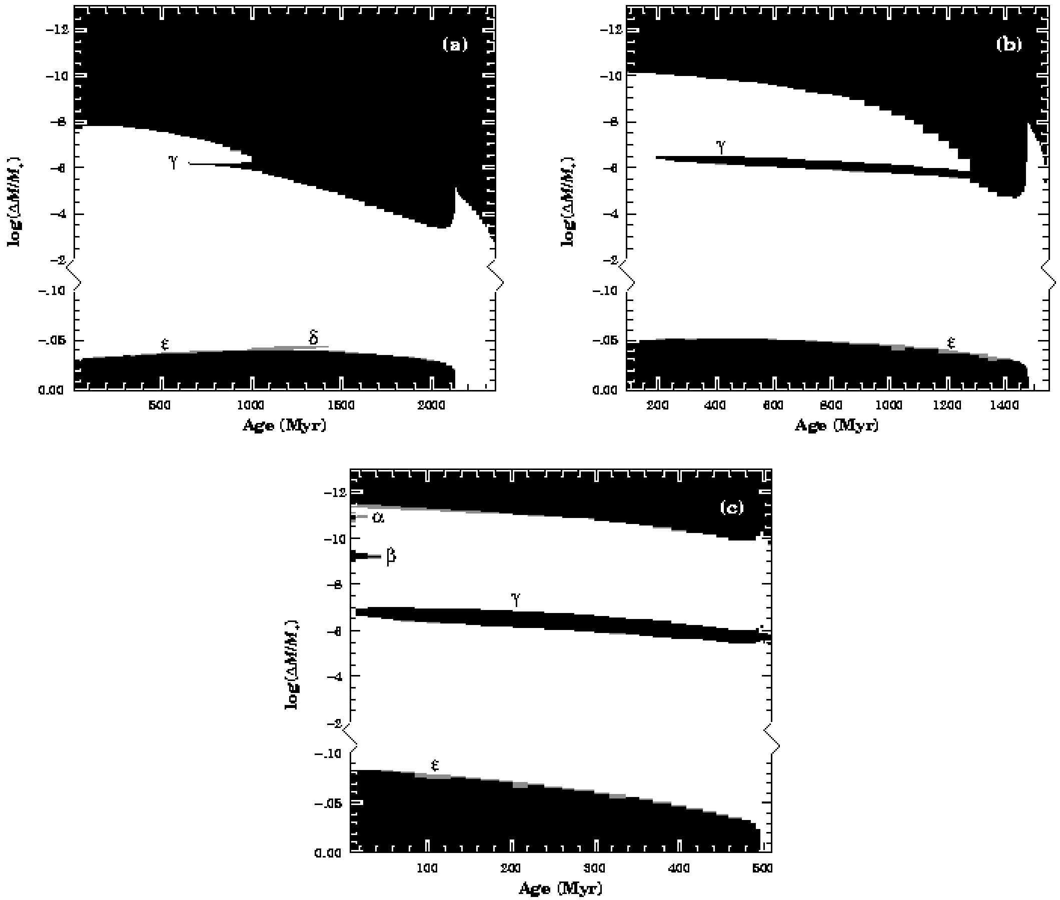


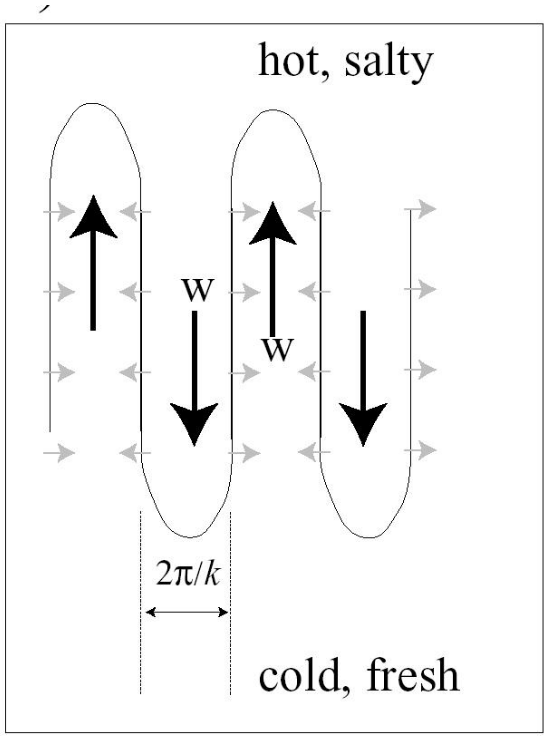
FIG. 8.—Convection and semiconvection zones in three models with turbulence parameterized by 5.3D50-3: (*a*) 1.5 $M_{\odot}$, (*b*) 1.7 $M_{\odot}$, and (*c*) 2.5 $M_{\odot}$. The radiative zones are in white, the convection zones in black, and the semiconvection zones in gray. The convection zones α and β, due to He I and II, rapidly disappear because of He settling. The convection zone γ is the Fe convection zone. Close to the central convective core, there appear semiconvection zones, ε and δ.

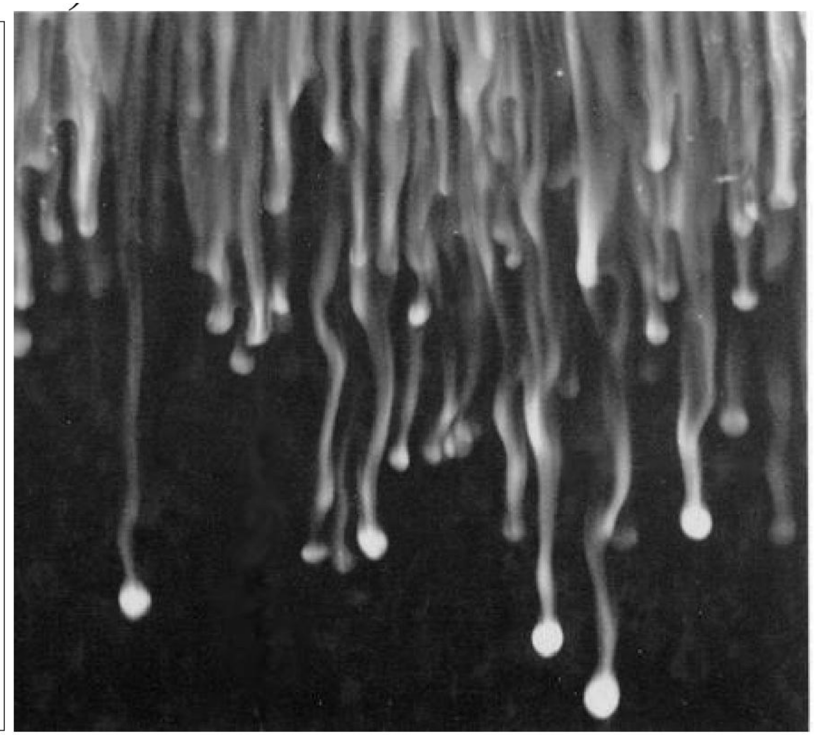
Richard, Michaud et al

Institute of Theoretical Astronomy, Cambridge

International symposium on « supermassive stars »
July 1971

thermohaline convection

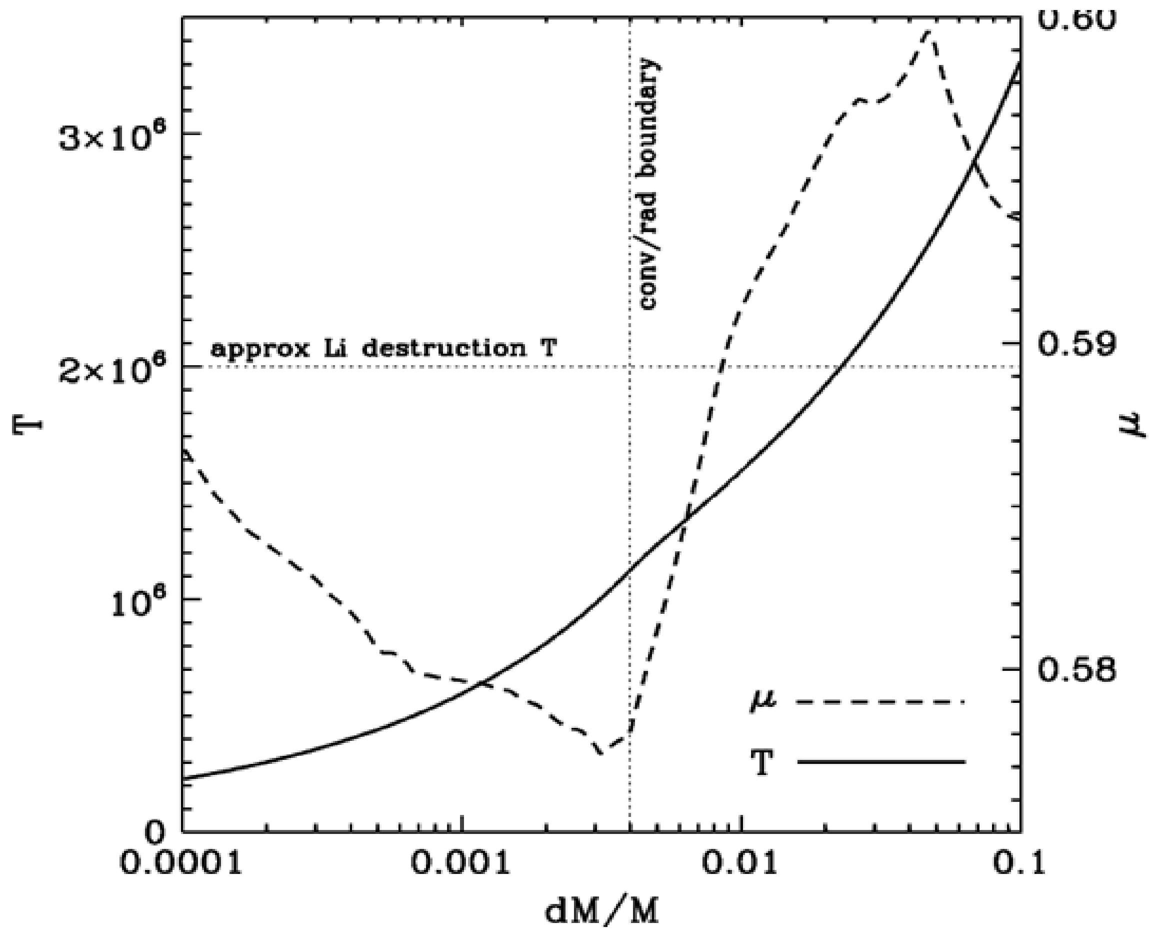




C.f. Pascale Garaud

CS22964-161

A Metal-poor Double-lined Spectroscopic Binary with C, Li, and s-process Overabundances



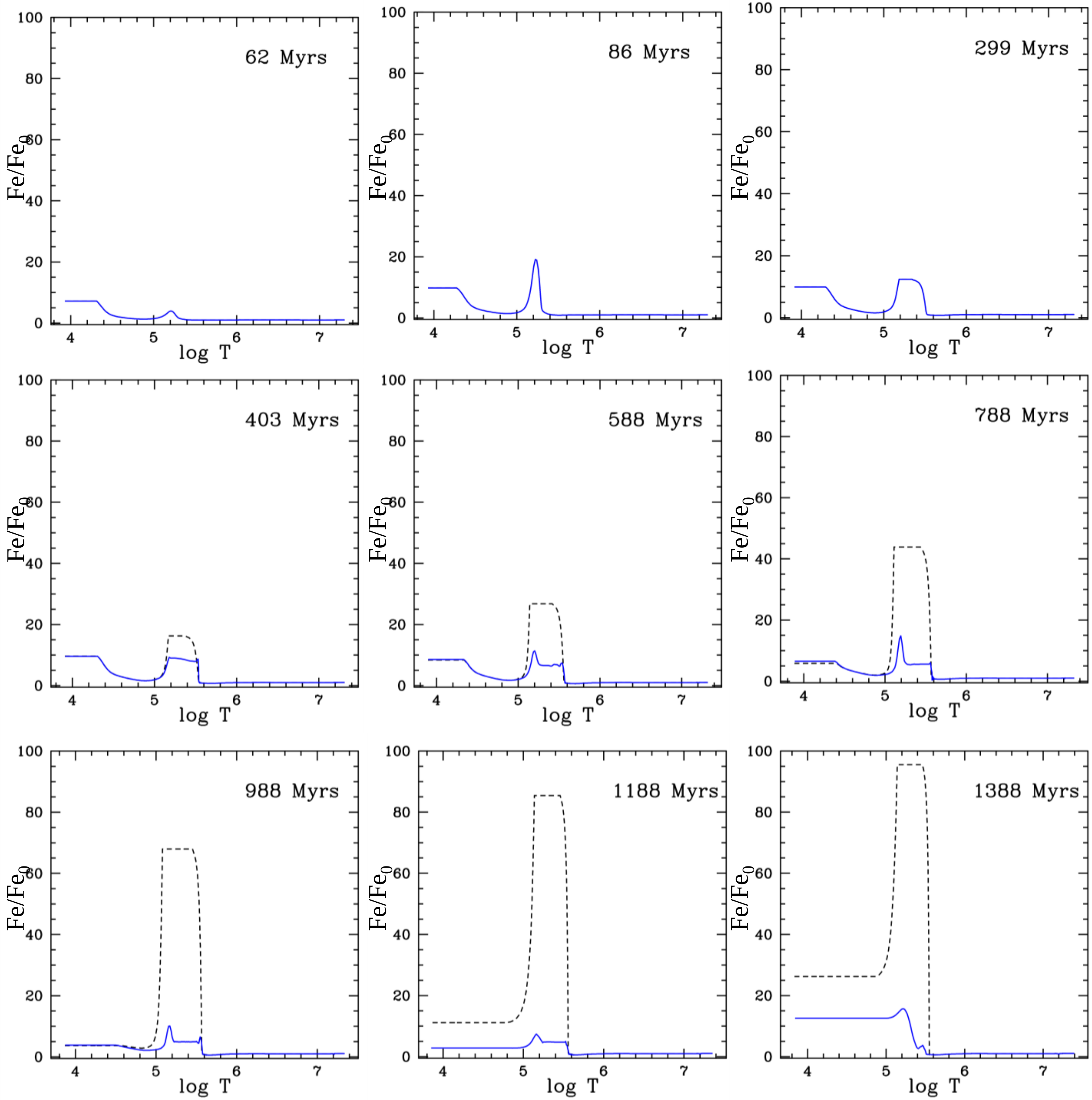
Thompson (Ian!!!) et al. 2008

Thompson, Ian B.; Ivans, Inese I.; Bisterzo, Sara;
Sneden, Christopher; Gallino, Roberto; Vauclair, Sylvie;
Burley, Gregory S.; Shectman, Stephen A.;Preston, George W.

Théado, Vauclair, Alecian, Leblanc, ApJ 704, 1262, 2009

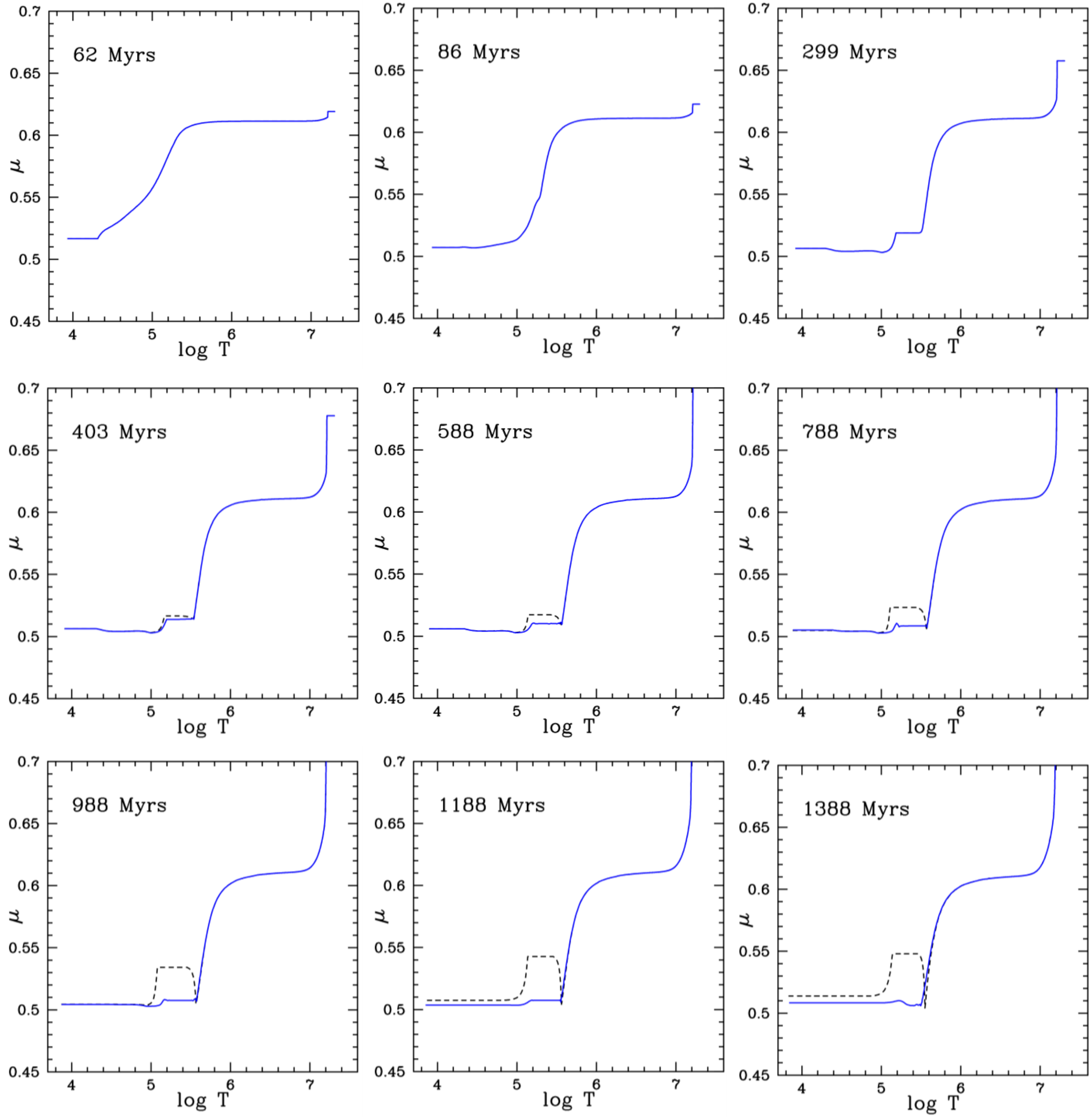
1.7 $M_\odot$

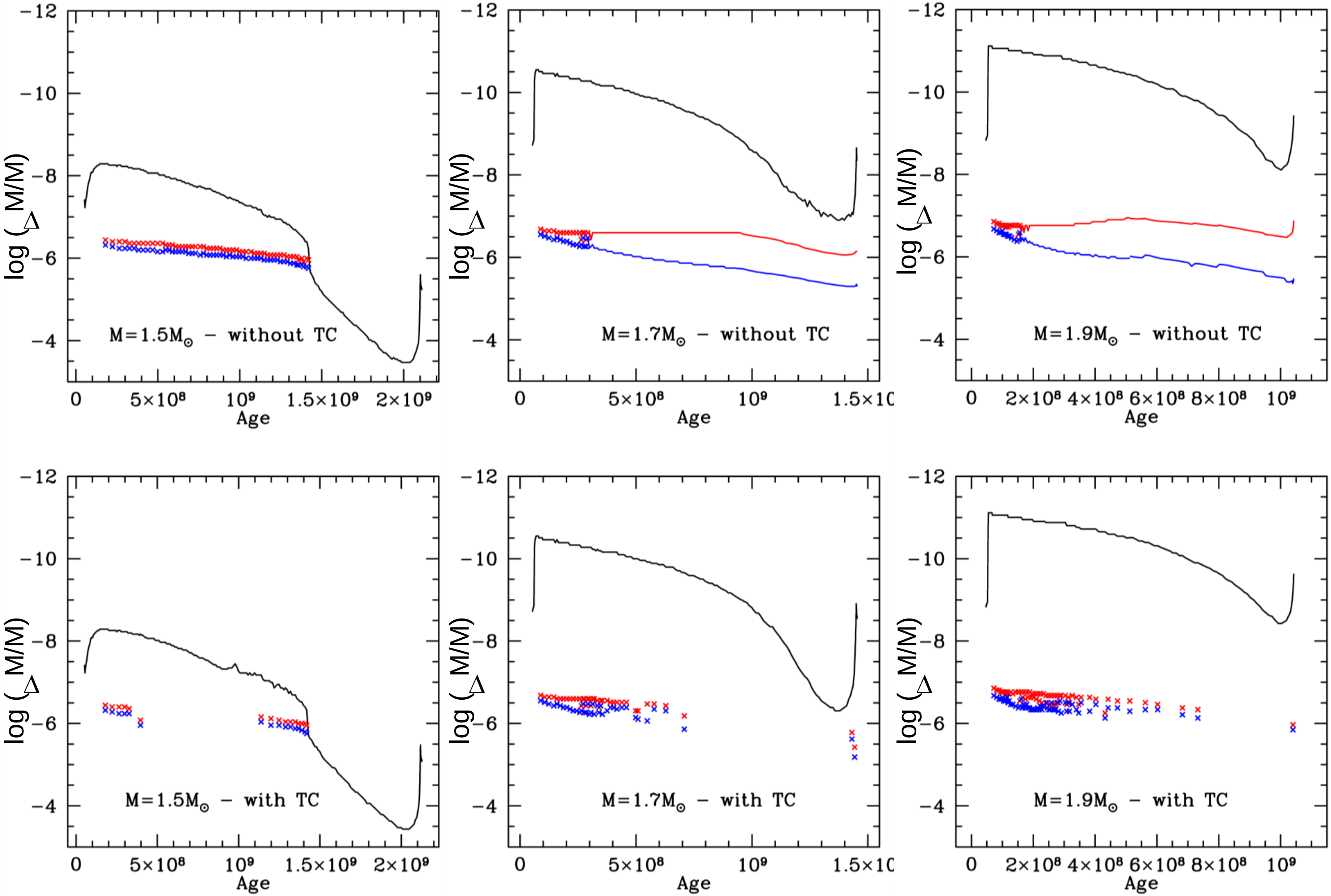
Fe/Fe_0



1.7 $M_\odot$

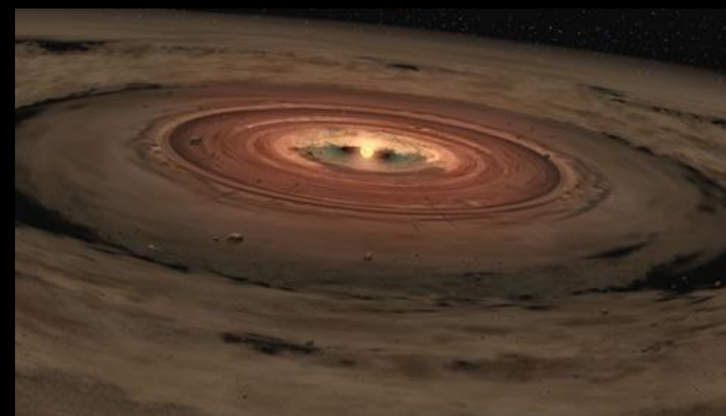
μ

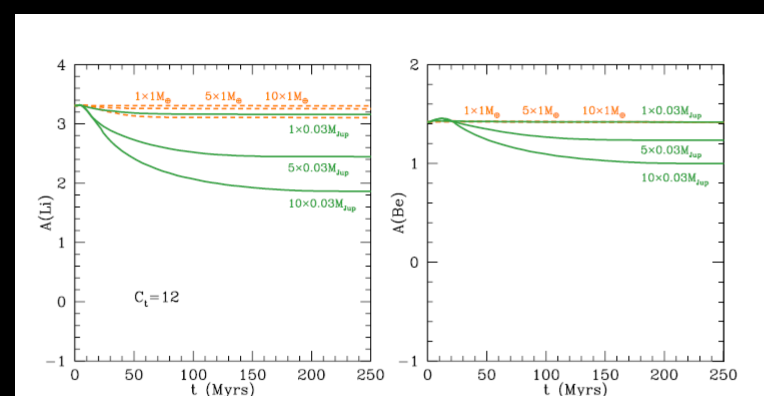

62 Myrs
86 Myrs
299 Myrs
403 Myrs
588 Myrs
788 Myrs
988 Myrs
1188 Myrs
1388 Myrs
μ
log T
0.45
0.5
0.55
0.6
0.65
0.7
4
5
6
7



M=1.5M⊙ – without TC
M=1.7M⊙ – without TC
M=1.9M⊙ – without TC
M=1.5M⊙ – with TC
M=1.7M⊙ – with TC
M=1.9M⊙ – with TC
log (ΔM/M)
Age

What's next ?





C.f. Vauclair 2004
Théado, Bohuon, Vauclair 2010
Garaud 2011 (see also Traxler et al. 2011)
Théado & Vauclair , submitted to ApJ