Du nouveau dans les étoiles…

Sylvie Vauclair

Michael Bazot, Matthieu Castro, Marion Laymand, Mélanie Soriano, Maria-Eliana Escobar, Morgan Deal

Georges Alecian, Alain Hui-Bon-Hoa, Olivier Richard, Sylvie Théado,
Gérard Vauclair, Felipe Wachlin

Nice, 17 novembre 2015

Two important physical processes have been forgotten for many years in the studies of stellar structure and evolution:

- Atomic diffusion including radiative accelerations

  (this physical process was introduced a few decades ago to account for the « chemically peculiar stars » but its importance inside stars was bypassed)

- fingering (thermohaline) convection induced by inverse μ-gradients

  (leads to extra mixing in various cases)

Outline

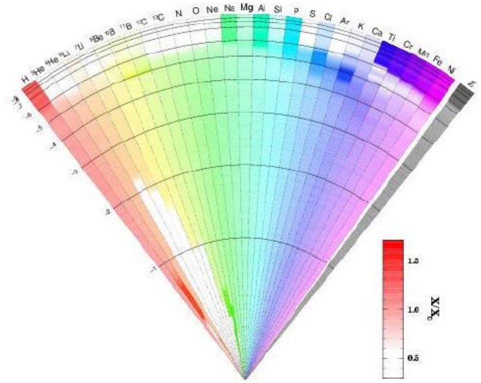
- Computations of atomic diffusion in stellar interiors:
  - include radiative accelerations
  - important results
- Fingering convection:
  - the physical process and 3D numerical simulations
  - consequences of atomic diffusion in MS stars
  - consequences of planetary matter accretion
  - the case of CEMP stars
  - Debris disks around white dwarfs : the fate of planetary systems

Outline

- Computations of atomic diffusion in stellar interiors:
    - include radiative accelerations
    - important results
- Fingering convection:
    - the physical process and 3D numerical simulations
    - consequences of atomic diffusion in MS stars
    - consequences of planetary matter accretion
    - the case of CEMP stars
    - Debris disks around white dwarfs : the fate of planetary systems

Atomic Diffusion in Stars

(Stars are non-uniform multi-component gases)



Basics of stellar physics : two kinds of processes in competition

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

Importance of precise microphysics for stellar structure and evolution

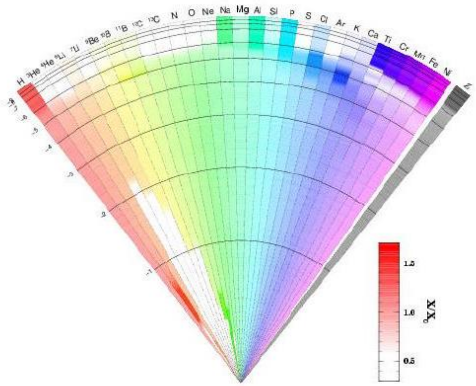
1) gravitational settling
2) thermal diffusion
3) concentration gradients
4) radiative accelerations

-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

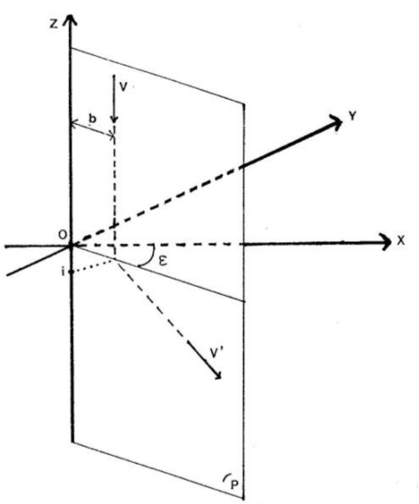
Chapman-Enskog description



Treatment of collisions (Boltzmann integro-differential equation):

$[f(\mathbf{c}+\boldsymbol{F}dt,\ \boldsymbol{r}+\mathbf{c}dt,\ t+dt) - f(\mathbf{c},\boldsymbol{r},t)] = (collision\ term)$

f (c,r,t) is the distribution function of the particles, i.e. the number of particles in the volume element (**r**, **r+dr**) with velocities in the range (**c**, **c+dc**) at time t

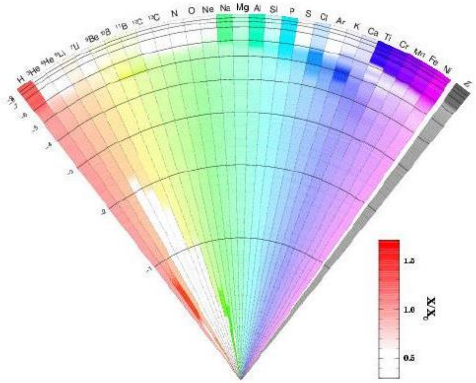


$$\left(\frac{\partial f_i}{\partial t}\right)_{col} = \iiint (f_i' f_j' - f_i f_j)\ \boldsymbol{v}\ b\ db\ d\varepsilon\ \mathbf{dc_j}$$

Maxwellian ($\left(\frac{\partial f_i}{\partial t}\right)_{col} = 0$) : $f_i' f_j' = f_i f_j$

in the presence of gradients ($\left(\frac{\partial f_i}{\partial t}\right)_{col} \neq 0$) : $f_i' f_j' \neq f_i f_j$

Compute the collision integrals as a development in terms of small knudsen number $k = l/L = t_{mic}/t_{mac}$



derived equations:

Diffusion equation:

$$\frac{\partial(\rho c_i)}{\partial t} + div(\rho c_i v_i) = 0$$

for test atoms:
(including mixing coefficient Dth)

$$v_i = D_i\left(-\frac{D_i + D_{th}}{D_i}\nabla \ln c + k_P \nabla \ln P + k_T \nabla \ln T + \frac{m_i g_i}{kT}\right)$$

Approximate expressions (not used in codes but interesting for physical discussions):

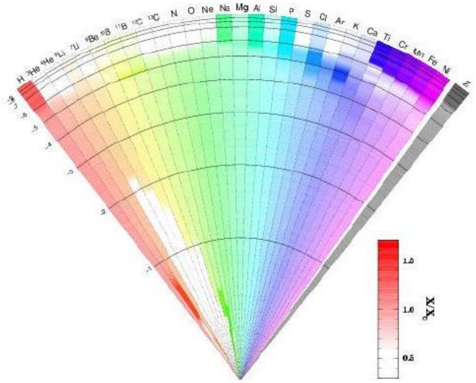
$$v_d = -D\left[\frac{1}{c}\frac{\partial c}{\partial r} - \frac{m(g_R - g_{GT})}{kT}\right]$$

with:

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

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

Burgers diffusion equations



$$\frac{\mathrm{d}p_i}{\mathrm{d}r} + \rho_i(g - g_{\mathrm{rad},i}) - n_i \bar{Z}_i e E =$$

$$\sum_{j\neq i}^{N} K_{ij}(w_j - w_i) + \sum_{j\neq i}^{N} K_{ij} z_{ij} \frac{m_j r_i - m_i r_j}{m_i + m_j},$$

including the heat flow equations,

$$\frac{5}{2} n_i k_{\mathrm{B}} \nabla T = \frac{5}{2} \sum_{j\neq i}^{N} z_{ij} \frac{m_j}{m_i + m_j}(w_j - w_i) - \frac{2}{5} K_{ii} z''_{ii} r_i$$

$$- \sum_{j\neq i}^{N} \frac{K_{ij}}{(m_i + m_j)^2}(3m_i^2 + m_j^2 z'_{ij} + 0.8 m_i m_j z''_{ij}) r_i$$

$$+ \sum_{j\neq i}^{N} \frac{K_{ij} m_i m_j}{(m_i + m_j)^2}(3 + z'_{ij} - 0.8 z''_{ij}) r_j.$$

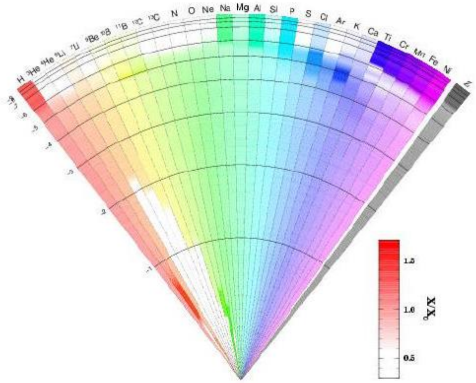
In addition, we have two constraints, current neutrality,

$$\sum_i \bar{Z}_i n_i w_i = 0$$

and local mass conservation,

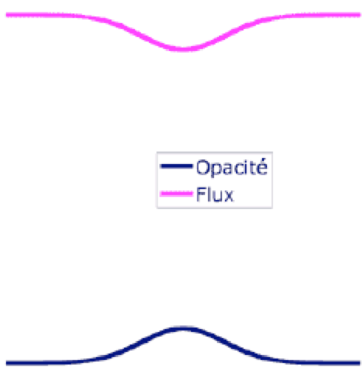
$$\sum_i m_i n_i w_i = 0.$$

Radiative accelerations :



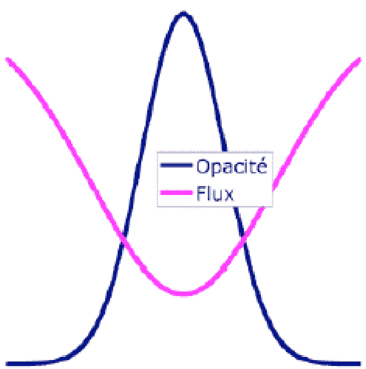
$$g_{i,n} = \frac{1}{m_2 N_2} \frac{4\pi}{3c} \left(-\frac{\partial T}{\partial r}\right) \left[\frac{\partial B_\nu}{\partial T}\right]_{\nu_0} \int_{-\infty}^{+\infty} \frac{N_{i,n} \frac{\pi e^2}{m_e c} f_{n,m} g(\nu) d\nu}{\varkappa_\nu(R)\rho + N_{i,n} \frac{\pi e^2}{m_e c} f_{n,m} g(\nu)}$$

unsaturated line



g_{rad} independent of N

saturated line



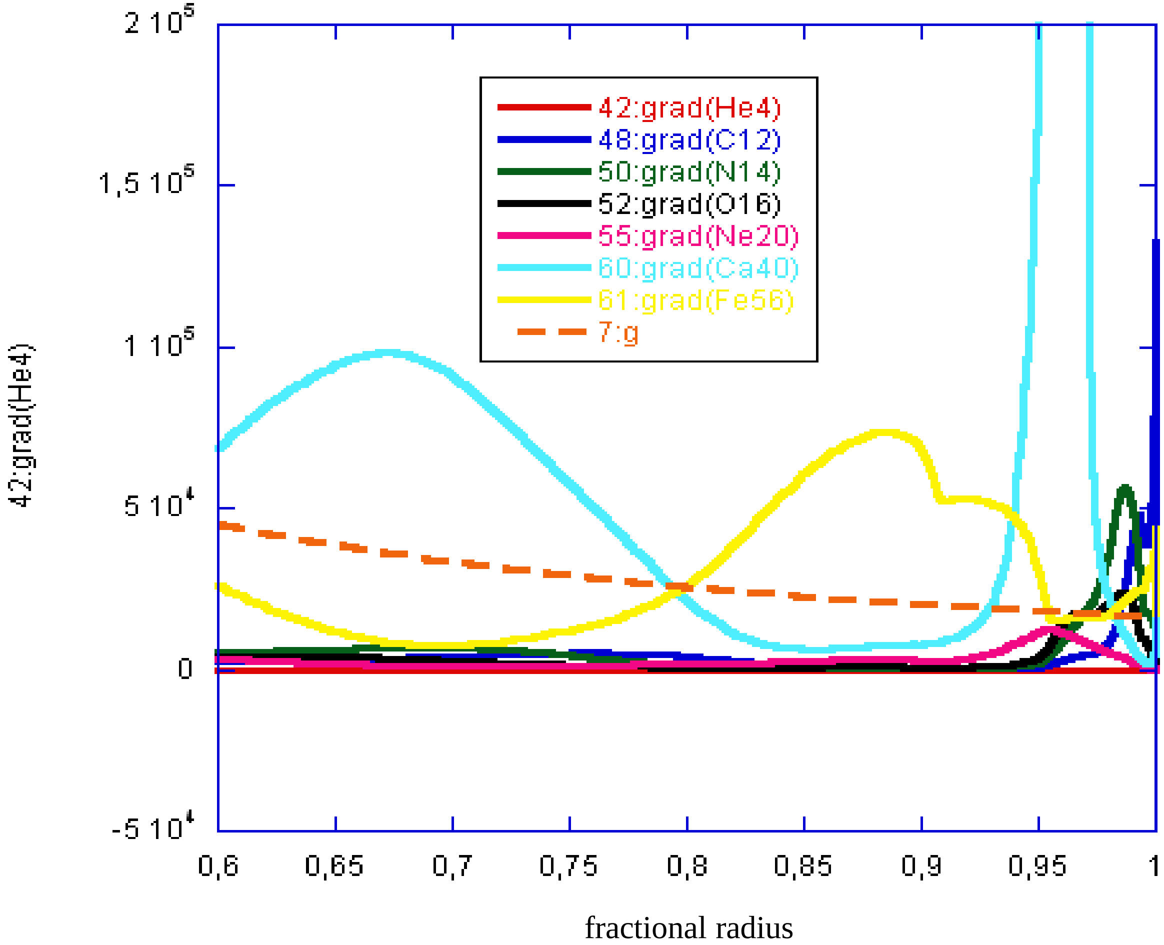
g_{rad} ↑ when N↓

Montreal-Montpellier code :
Complete computations of radiative accelerations using OPAL detailed opacity computations

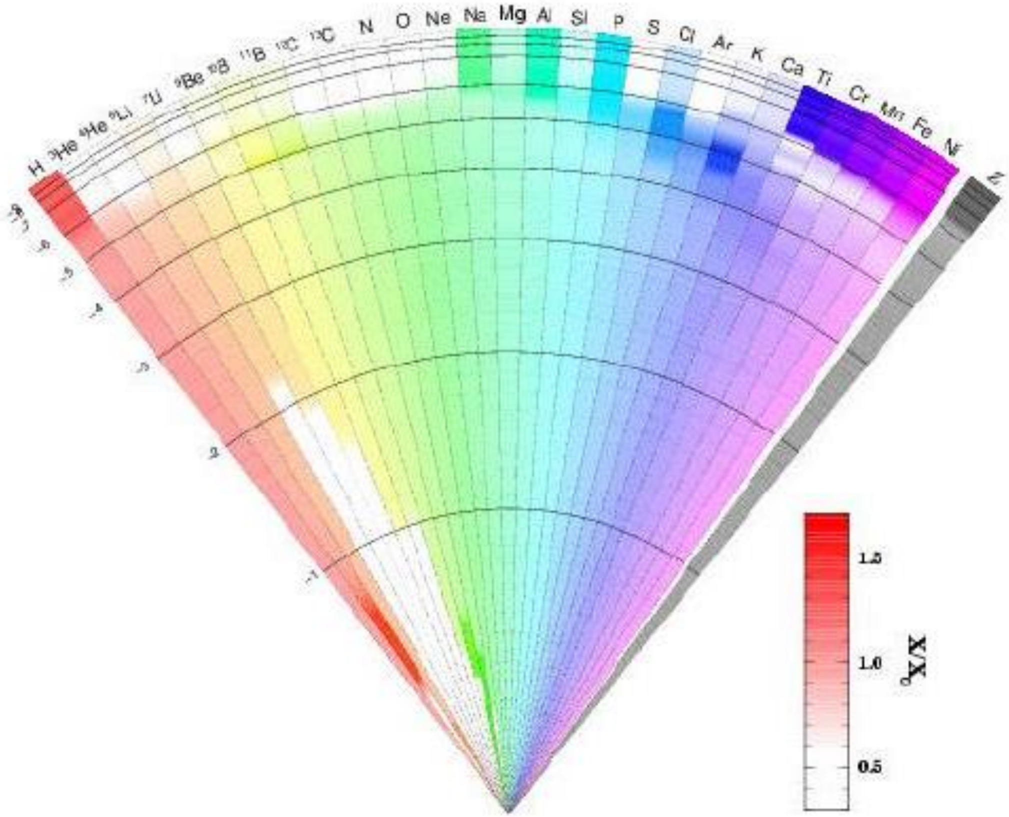
TGEC code:
Approximate computations using SVP (sigle-valued parameters) method (Alecian-Leblanc) and OP opacity computations

Other possibility: OP package (tables)

Radiative accelerations in an A star, 1.7Msun, 403 Myr



(TGEC code, Théado & Vauclair)

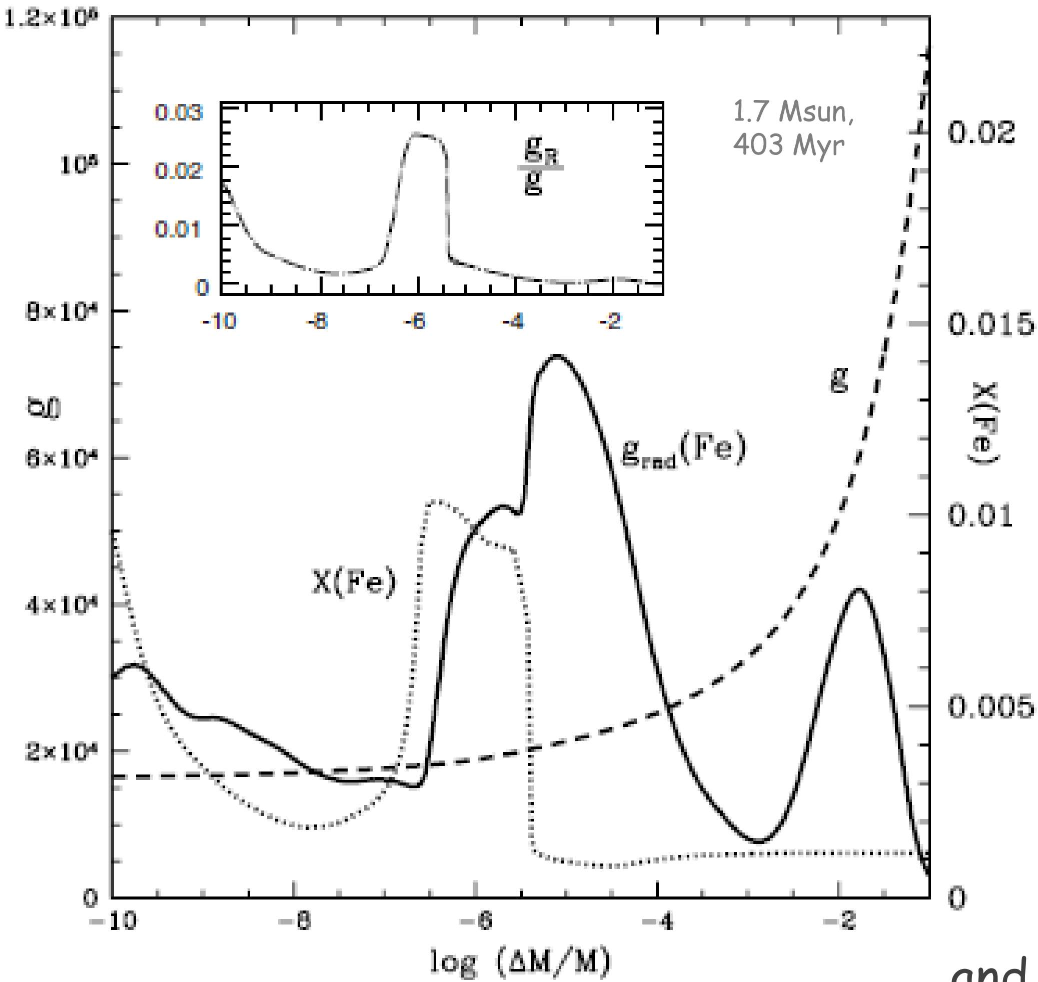


Examples of color intensity
coded elements concentrations
after pure diffusion : 3Msun, 70Myr
(Richer et al. 1999)

Possible macroscopic consequences of atomic diffusion:
(other than observed abundances)

- dynamical convection
- thermohaline convection
- stellar oscillations

Mic-mac connection:



(Vauclair and Théado 2012)

Assume one element *i* : g_R(i) > g
where $g_R(i) = \sum_j X_{i,j} g_{i,j}$

Contribution to the total radiative acceleration on the medium:
$g_R = X_i g_R$(i)

Most often: g_R < g

effective gravity: $g_e = \mathrm{g} - g_R \cong g$

BUT!
The accumulation of the element and the collisions with the surroundings lead to an increase of μ

… and to an increase of the local opacity!!!

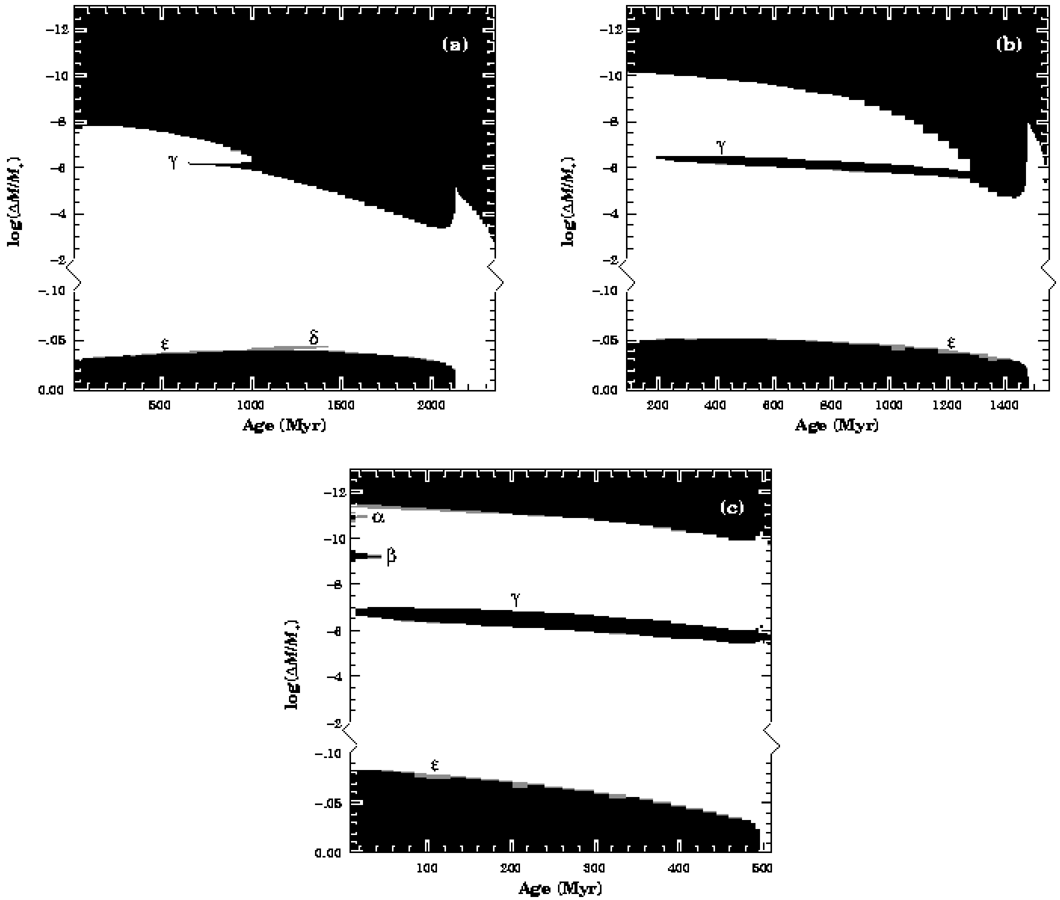


FIG. 8.—Convection and semiconvection zones in three models with turbulence parameterized by 5.3D50-3: (*a*) 1.5 $M_\odot$, (*b*) 1.7 $M_\odot$, and (*c*) 2.5 $M_\odot$. The radiative zones are in white, the convection zones in black, and the semiconvection zones in gray. The convection zones α and β, 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, Richer 2001

Outline

- Computations of atomic diffusion in stellar interiors:
    - include radiative accelerations
    - important results
- Fingering convection:
    - the physical process and 3D numerical simulations
    - consequences of atomic diffusion in MS stars
    - consequences of planetary matter accretion
    - the case of CEMP stars
    - Debris disks around white dwarfs : the fate of planetary systems

Thermohaline convection: the ocean case

Define the density anomaly ratio as :

$$R_\rho = \alpha\nabla T/\beta\nabla S$$

where :

$$\alpha = (1/\rho)(\partial\rho/\partial T)_{S,P}$$

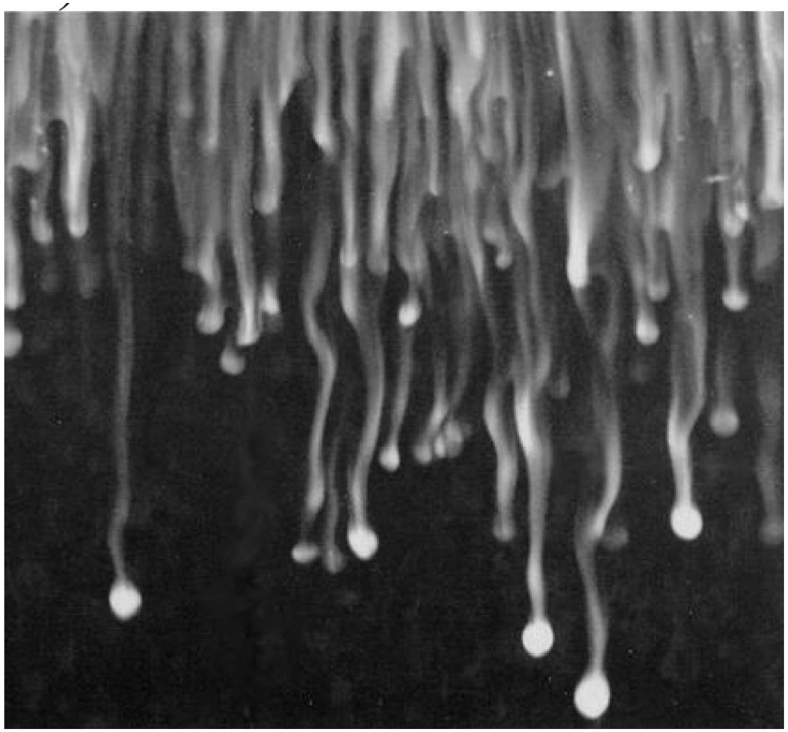
$$\beta = (1/\rho)(\partial\rho/\partial S)_{T,P}$$

and the lewis number :

$$\tau = \kappa_S/\kappa_T \; = \; t_T/t_S$$

salt fingers can grow if :

$$1 \leq R_\rho \leq \tau^{-1}$$



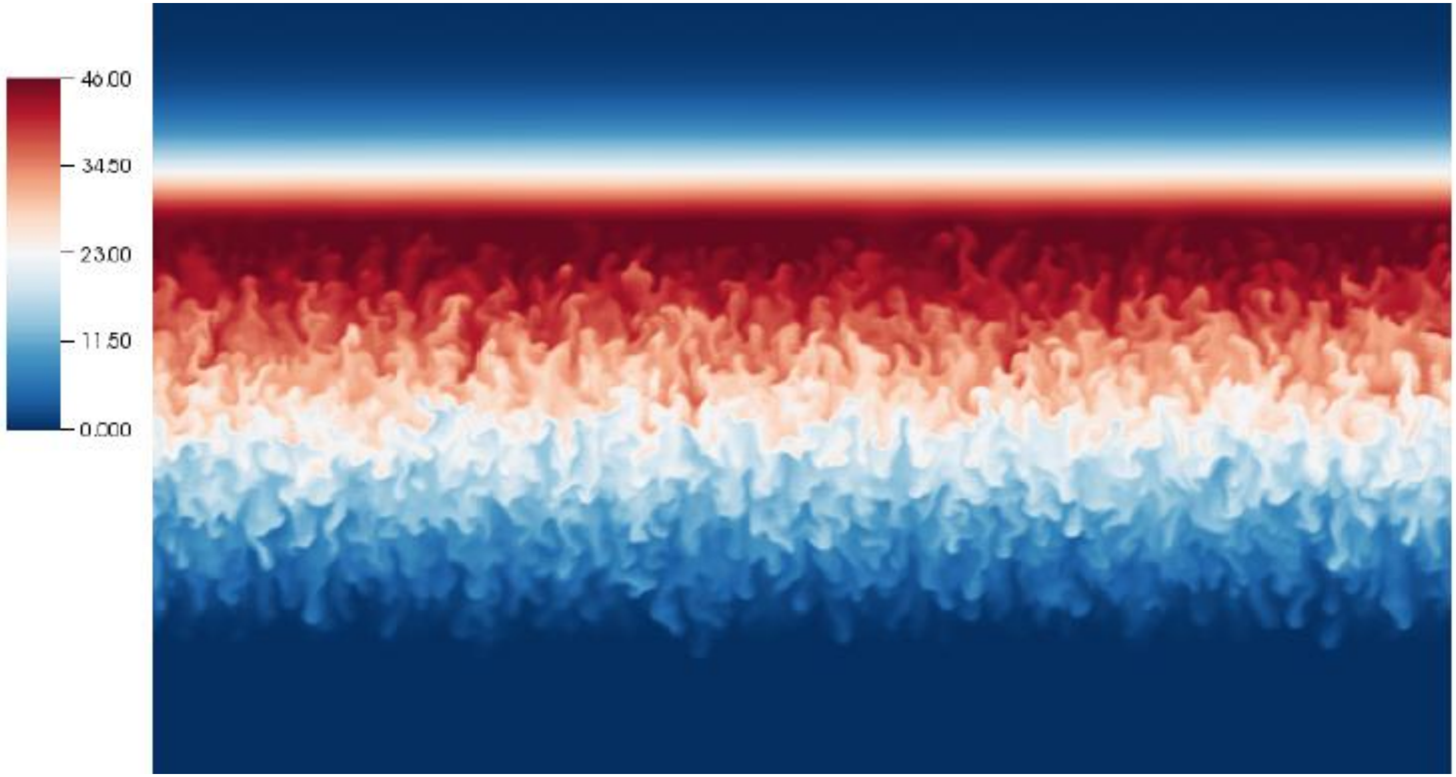
Stern 1960, Kato 1966, Veronis 1965, Turner 1973, Turner and Veronis 2000, Wells 2001, Piacsek and Toomre 1980, Shen and Veronis 1997, Yoshida and Nagashima 2003, Gargett and Ruddick 2003

Double-diffusion experiment (Pringle et al. 2002)

sucrose solution above denser sodium chlorine solution
diffusivity (salt) ≈ 3 diffusivity (sugar)

SCOTT E. PRINGLE, ROBERT J. GLASS, CLAY A. COOPER - Transport in Porous Media 47: 195–214, 2002

Mixing of an iron-rich layer with the gas below
(3D - numerical simulations)



Barbara Zemskova, Pascale Garaud, Morgan Deal, Sylvie Vauclair, Ap.J. 895, 118, 2014

The stellar case

∇_μ = $d\ln\mu/d\ln P$ plays the role of the salinity gradient;

∇_{rad}- ∇ plays the role of the temperature gradient

« fingers » form if :

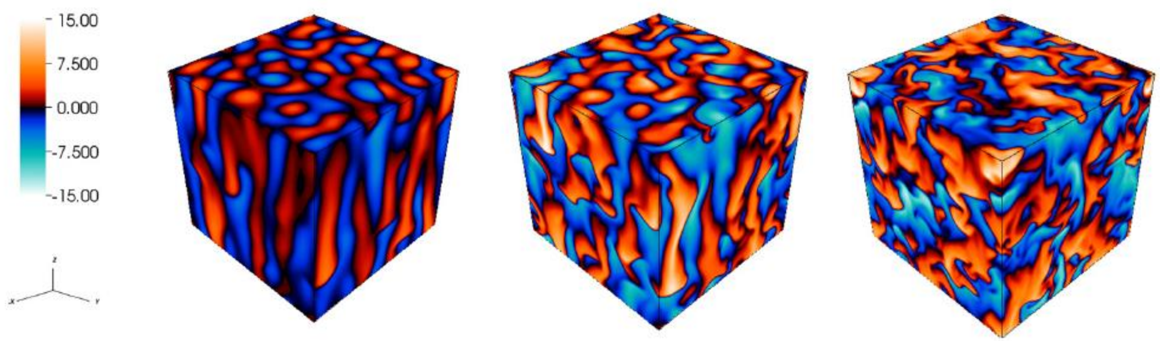
$$1 < R_0 < \frac{1}{\tau}$$

with: $$R_0 = \frac{\nabla_{ad} - \nabla_{rad}}{\nabla_\mu}$$

and $\tau = \kappa_\mu / \kappa_T = \tau_T / \tau_\mu$

For R_0<1, dynamical convection

For R_0=1/τ, dissipation



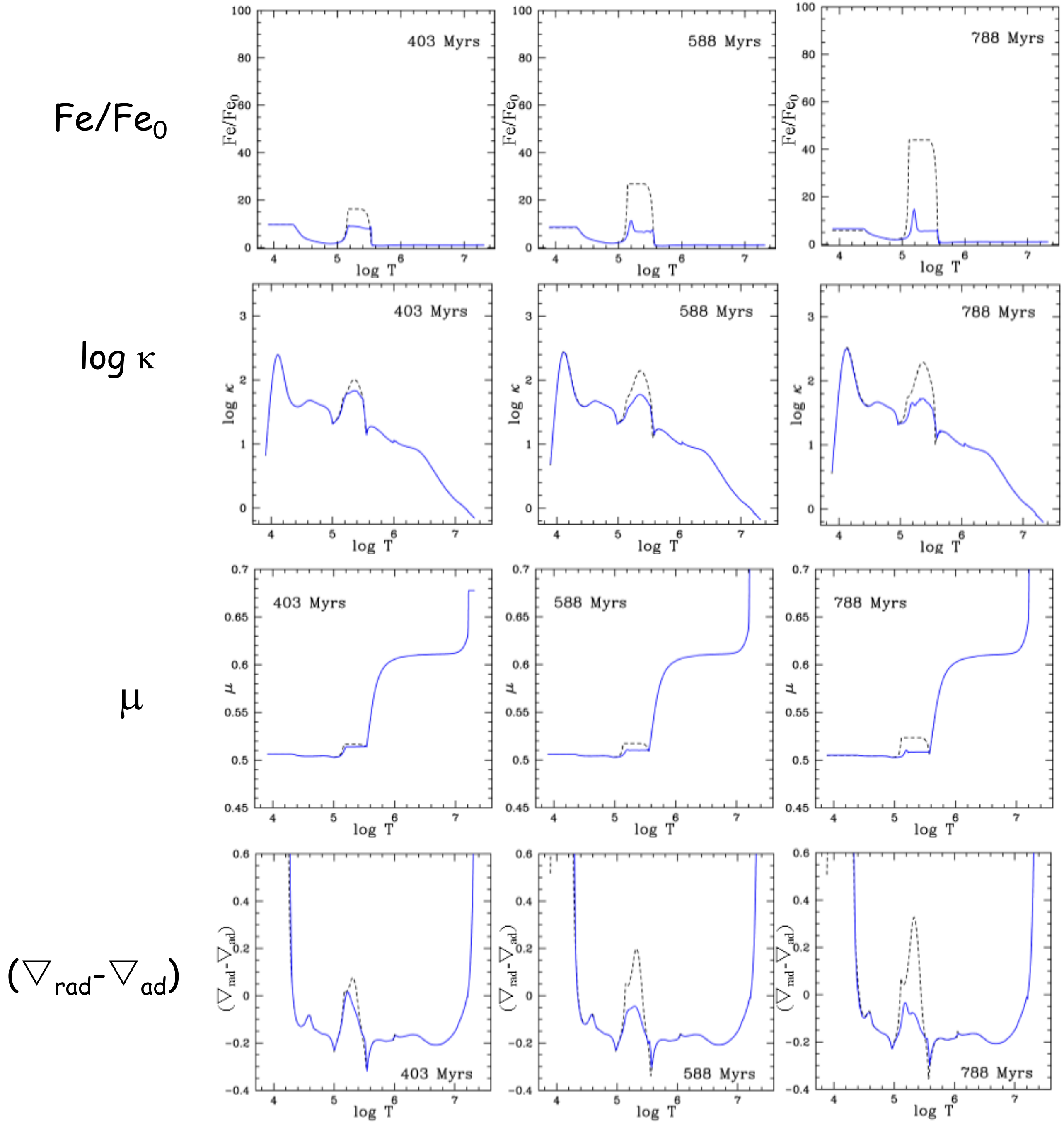
Simulations by Brown et al. 2013
R_0 = 3 ; Pr = 1/10; τ =1/ 30
reduced time: t=100 (prior to saturation)
155 (disrupted modes), 180 (saturated regime)

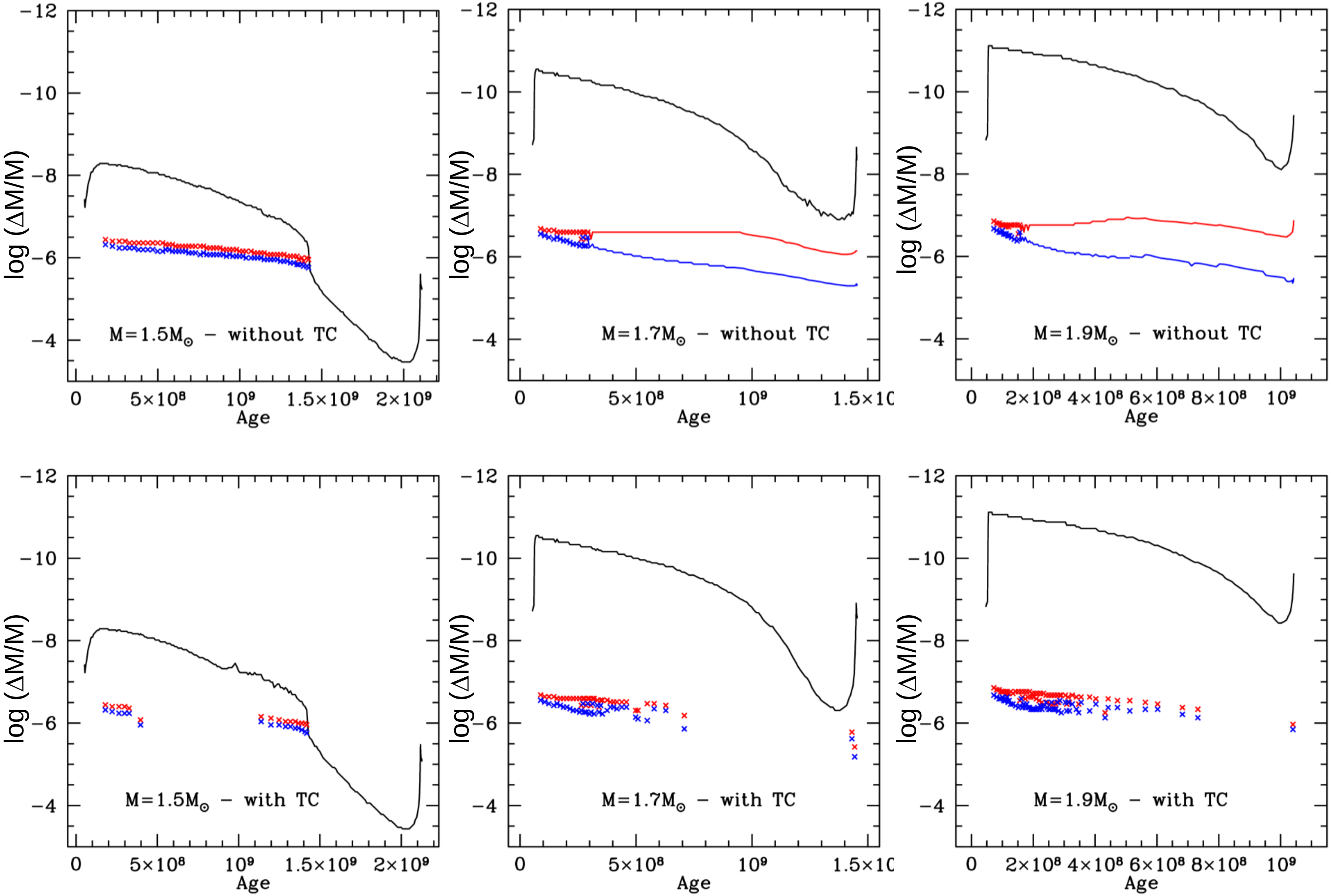
Outline

- Computations of atomic diffusion in stellar interiors:
    - include radiative accelerations
    - important results
- Fingering convection:
    - the physical process and 3D numerical simulations
    - consequences of atomic diffusion in MS stars
    - consequences of planetary matter accretion
    - the case of CEMP stars
    - Debris disks around white dwarfs : the fate of planetary systems

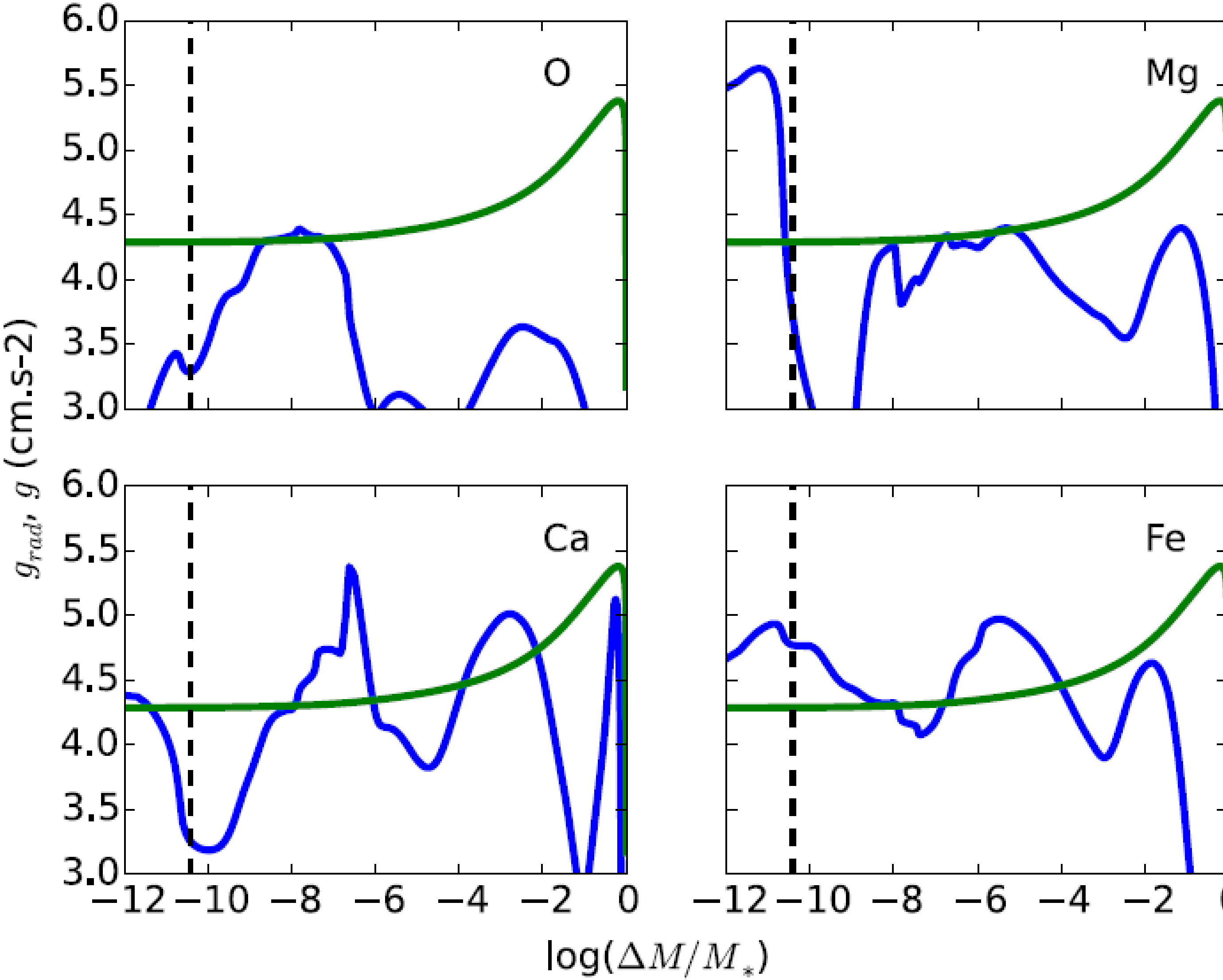
Théado, Vauclair, Alecian, Leblanc, 2009

1.7 $M_\odot$

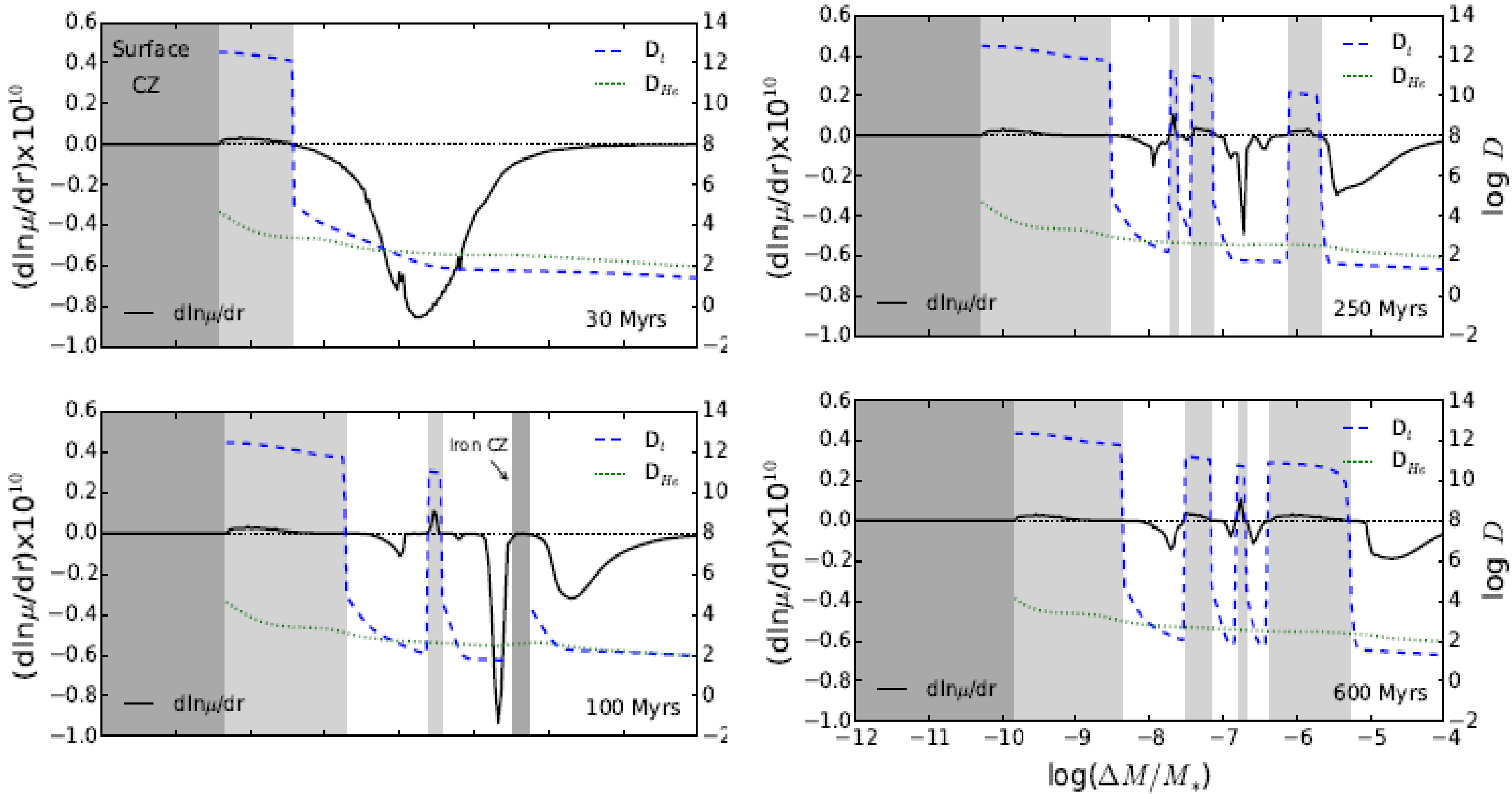




M=1.5M⊙ − without TC
M=1.7M⊙ − without TC
M=1.9M⊙ − without TC
M=1.5M⊙ − with TC
M=1.7M⊙ − with TC
M=1.9M⊙ − with TC
log (ΔM/M)
Age

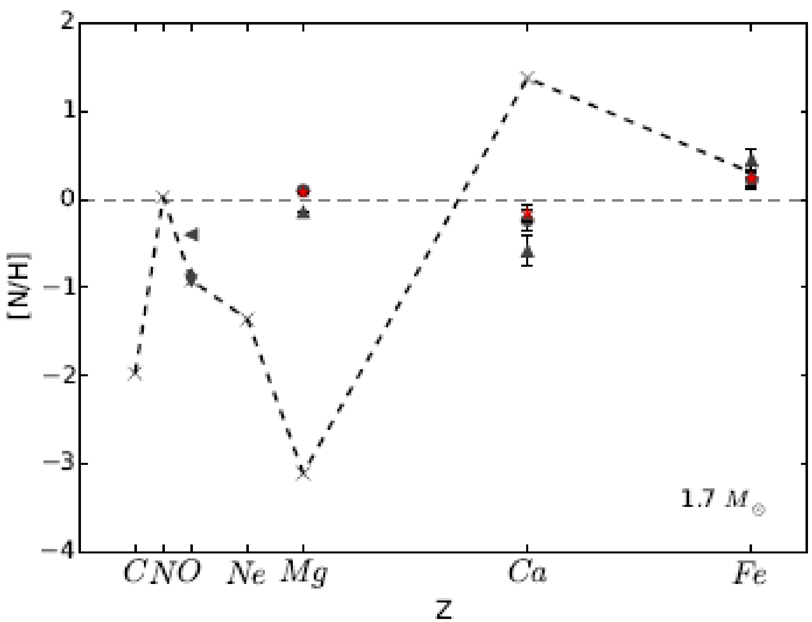


O
Mg
Ca
Fe
6.0
5.5
5.0
4.5
4.0
3.5
3.0
g_{rad}, g (cm.s-2)
−12
−10
−8
−6
−4
−2
0
log($\Delta M/M_*$)

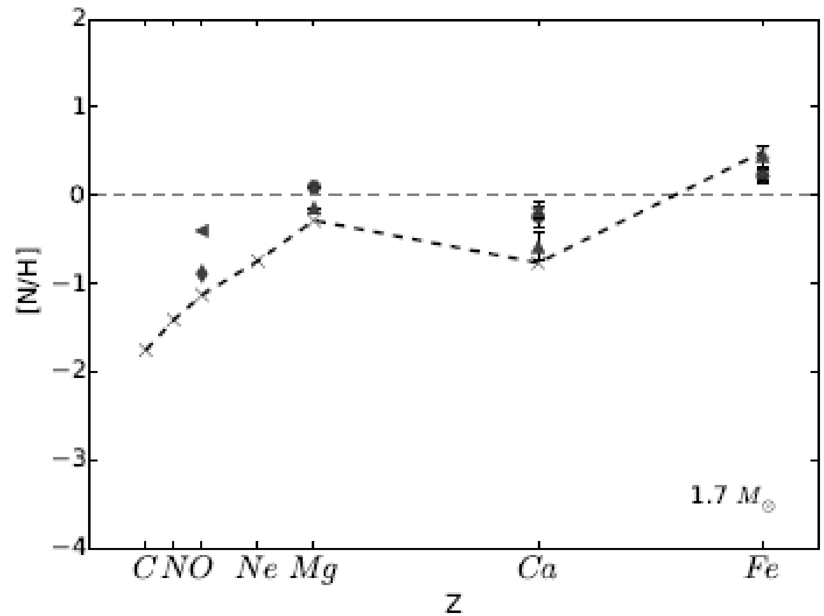


Deal et al, in prep. 1.7Msun

Disconnected fingering convection zones



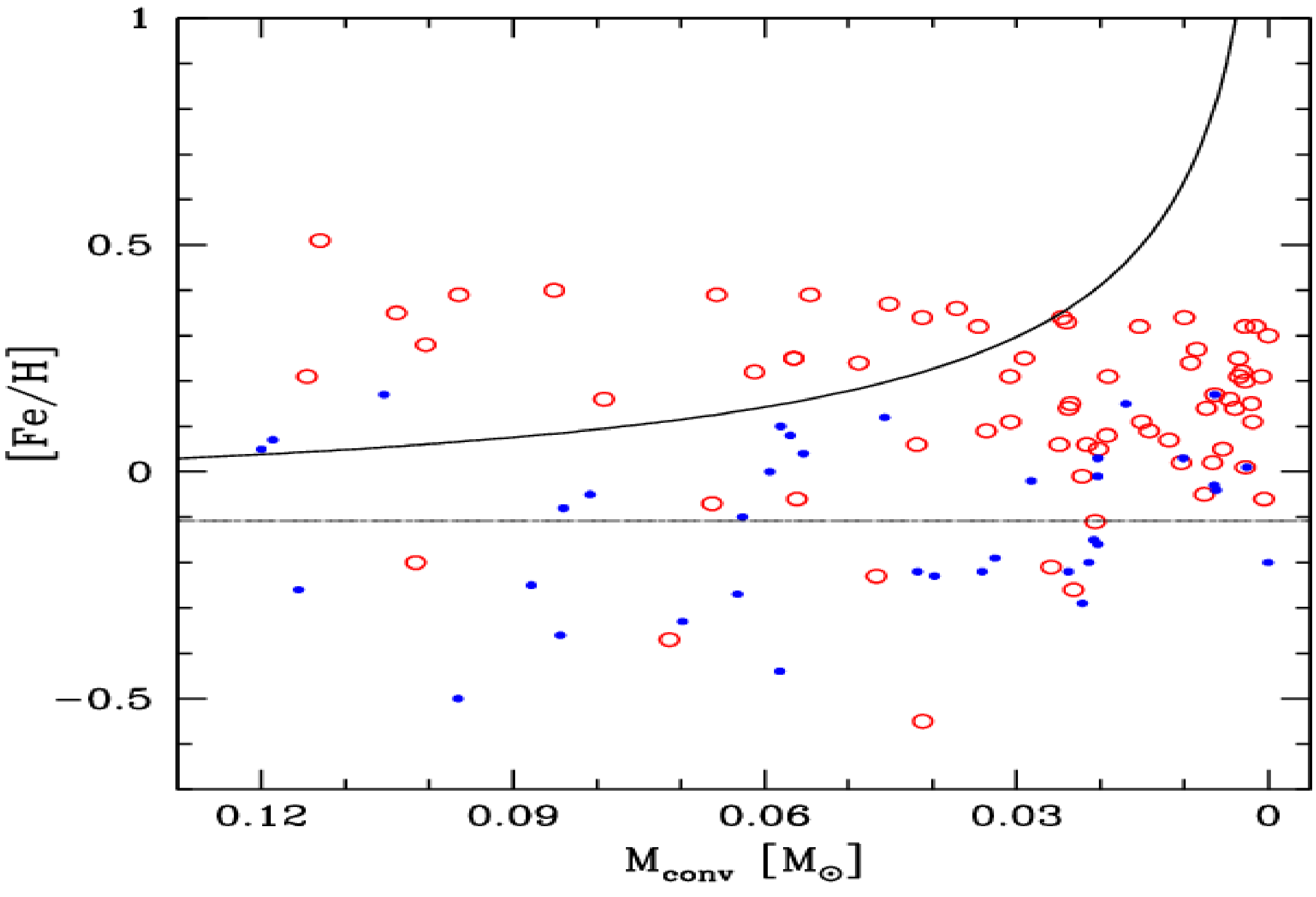
Connected fingering convection zones



Deal et al, in prep. 1.7Msun

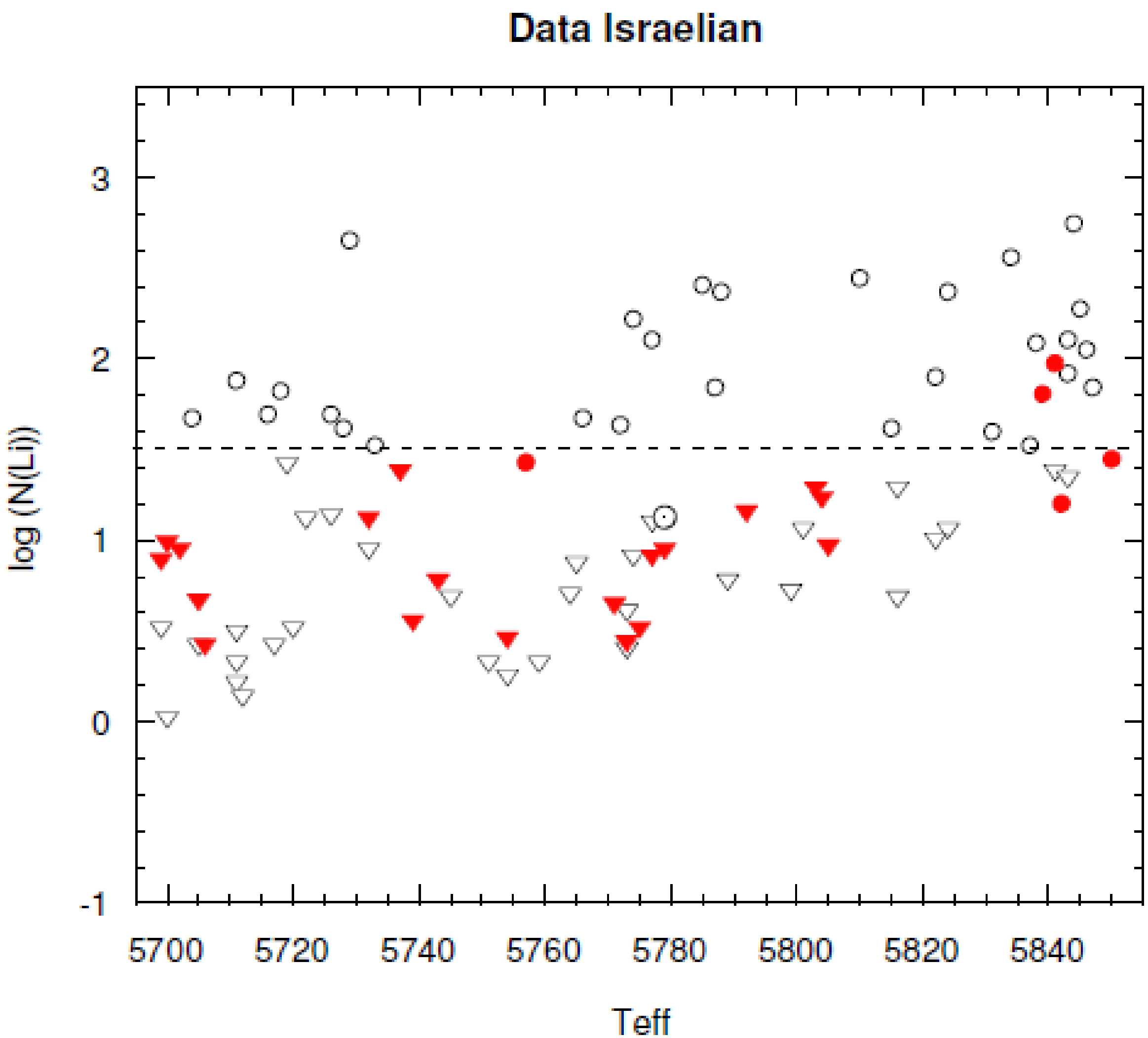
Outline

- Computations of atomic diffusion in stellar interiors:
  - include radiative accelerations
  - important results
- Fingering convection:
  - the physical process and 3D numerical simulations
  - consequences of atomic diffusion in MS stars
  - consequences of planetary matter accretion
  - the case of CEMP stars
  - Debris disks around white dwarfs : the fate of planetary systems



heavy elements in EHS: original abundances.

Observations: Santos et al. 2001, 2013; Théado & Vauclair 2012



Israelian et al, Nature 2010 (contestation: Melendez et al.)

Properties of 16 Cygni A and B from literature

	16 Cygni A	16 Cygni B
T_{eff}(K)	5825 ± 50[a]	5750 ± 50[a]
	5813 ± 18[b]	5749 ± 17[b]
	5796 ± 34[c]	5753 ± 30[c]
	5839 ± 42[d]	5809 ± 39[d]
	5830 ± 7[f]	5751 ± 6[f]
$\log g$	4.33 ± 0.07[a]	4.34 ± 0.07[a]
	4.282 ± 0.017[b]	4.328 ± 0.017[b]
	4.38 ± 0.12[c]	4.40 ± 0.12[c]
	4.30 ± 0.02[f]	4.35 ± 0.02[f]
[Fe/H]	0.096 ± 0.026[a]	0.052 ± 0.021[a]
	0.104 ± 0.012[b]	0.061 ± 0.011[b]
	0.07 ± 0.05[c]	0.05 ± 0.05[c]
	0.101 ± 0.008[f]	0.054 ± 0.008[f]
A(Li)	1.27 ± 0.05[i]	≤ 0.6[i]
A(Be)	0.99 ± 0.08[j]	1.06 ± 0.08[j]

	16 Cygni A	16 Cygni B
Mass ($M_\odot$)	1.05 ± 0.02[b]	1.00 ± 0.01[b]
	1.07 ± 0.05[d]	1.05 ± 0.04[d]
	1.11 ± 0.02[g]	1.07 ± 0.02[g]
Radius ($R_\odot$)	1.218 ± 0.012[d]	1.098 ± 0.010[d]
	1.22 ± 0.02[e]	1.12 ± 0.02[e]
	1.243 ± 0.008[g]	1.127 ± 0.007[g]
Luminosity ($L_\odot$)	1.56 ± 0.05[g]	1.27 ± 0.04[g]
Age (Gyrs)	$7.15^{+0.04}_{-1.03}$[b]	$7.26^{+0.69}_{-0.33}$[b]
	6.9 ± 0.03[g]	6.7 ± 0.03[g]
Z_i	0.024 ± 0.002[g]	0.023 ± 0.002[g]
Y_i	0.25 ± 0.01[g]	0.25 ± 0.01[g]
$v \sin i$ (km.s^{-1})	2.23 ± 0.07[h]	1.27 ± 0.04[h]
P_{rot} (days)	$23.8^{+1.5}_{-1.8}$[h]	$23.2^{+11.5}_{-3.2}$[h]
Planet detected	no	yes[k]

Deal et al, 2015 arXiv150906958

Ap.J., 744, 123, 2012

Metal-rich accretion and thermohaline instabilities in exoplanets-host stars: consequences on the light elements abundances

Sylvie Théado and Sylvie Vauclair[1]

Institut de Recherches en Astrophysique et Planétologie, Université de Toulouse, CNRS, 14 avenue Edouard Belin, 31400 Toulouse, France

stheado@ast.obs-mip.fr

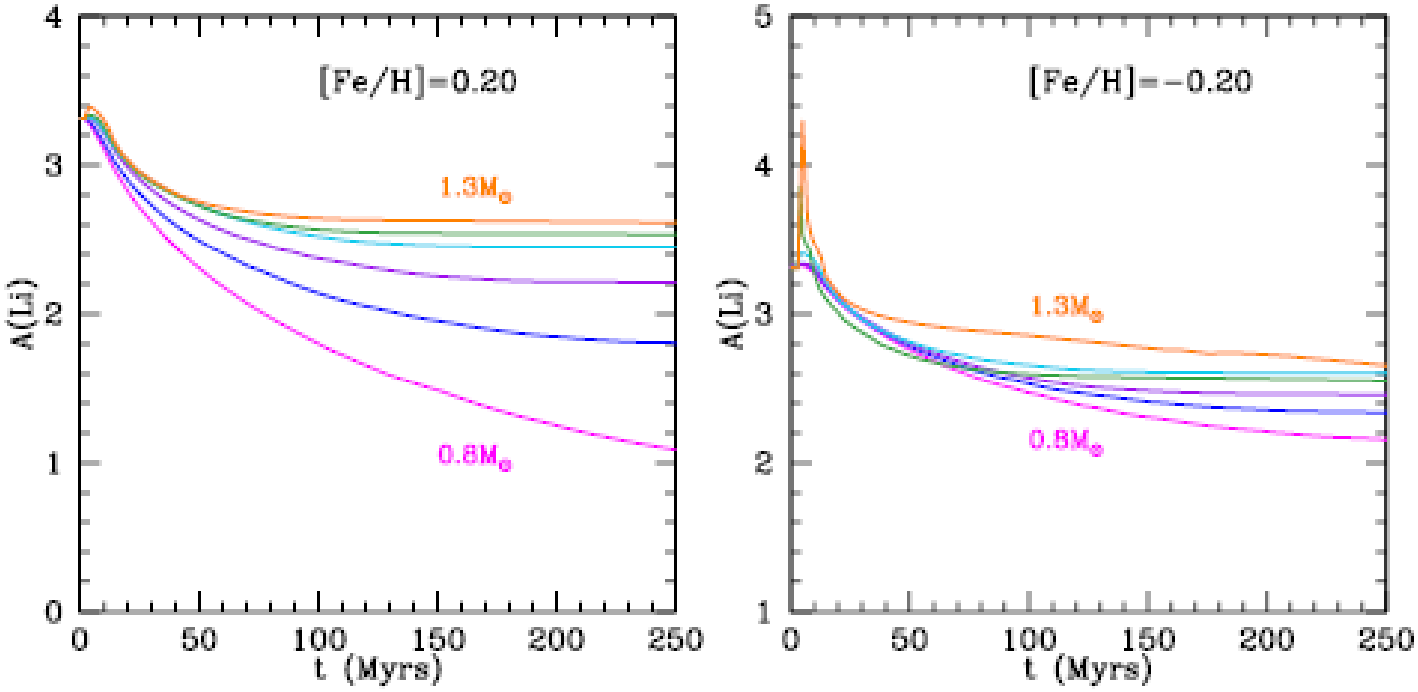
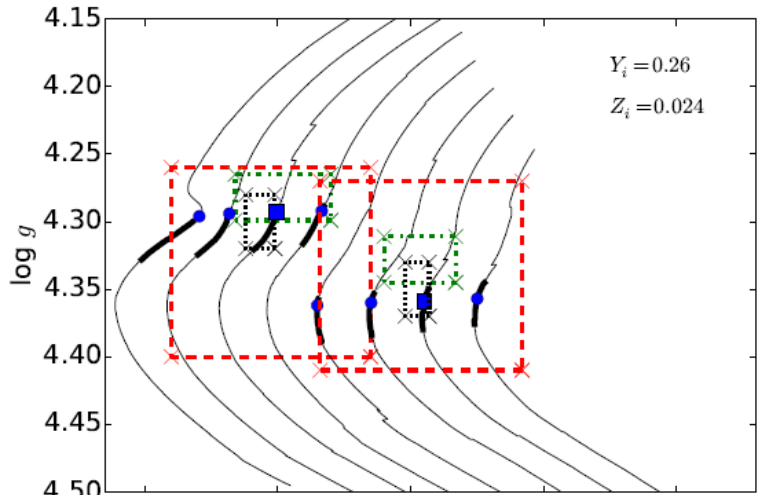
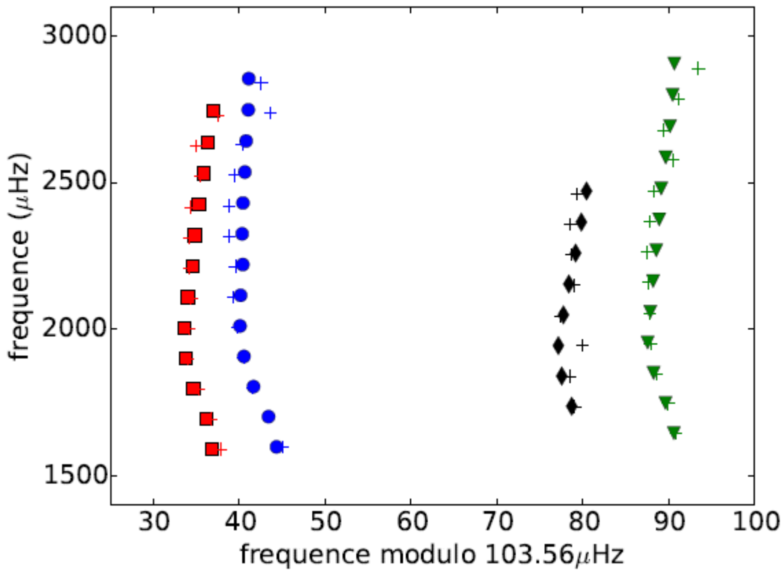


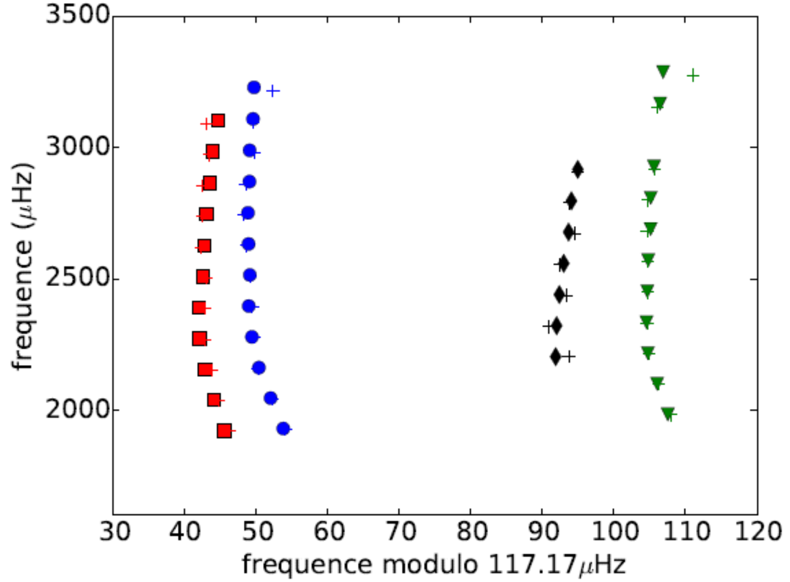
Fig. 6.— Lithium surface abundance over the accretion/mixing period in models experiencing 5 accretion episodes of $0.03M_{Jup}$. The presented models have different masses (0.8, 0.9, 1.0, 1.1, 1.2 and $1.3M_{\odot}$) and initial metallicities. These models have been computed with the KRT coefficient, C_t=12.

Seismic studies

16 Cyg A (left) 16 Cyg B (right)

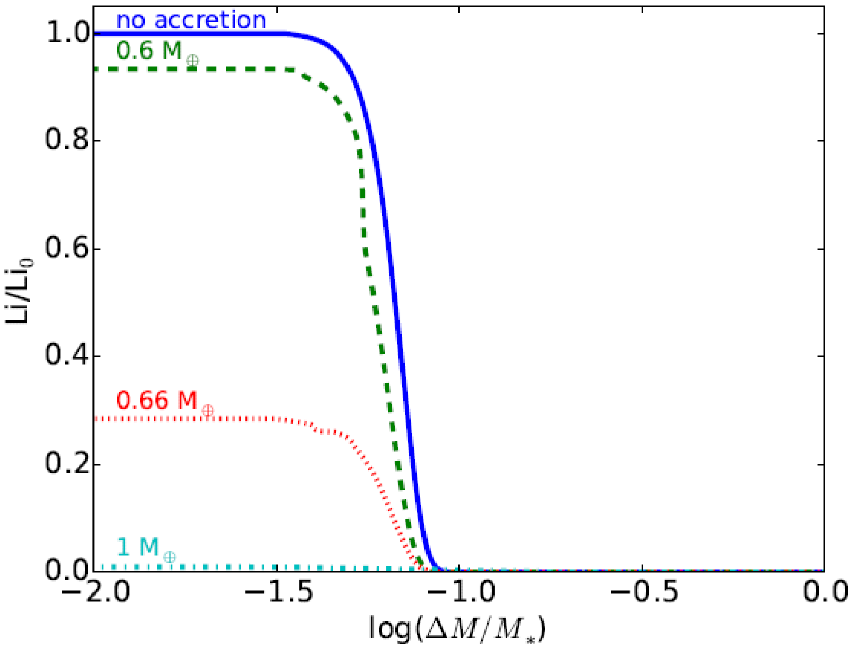




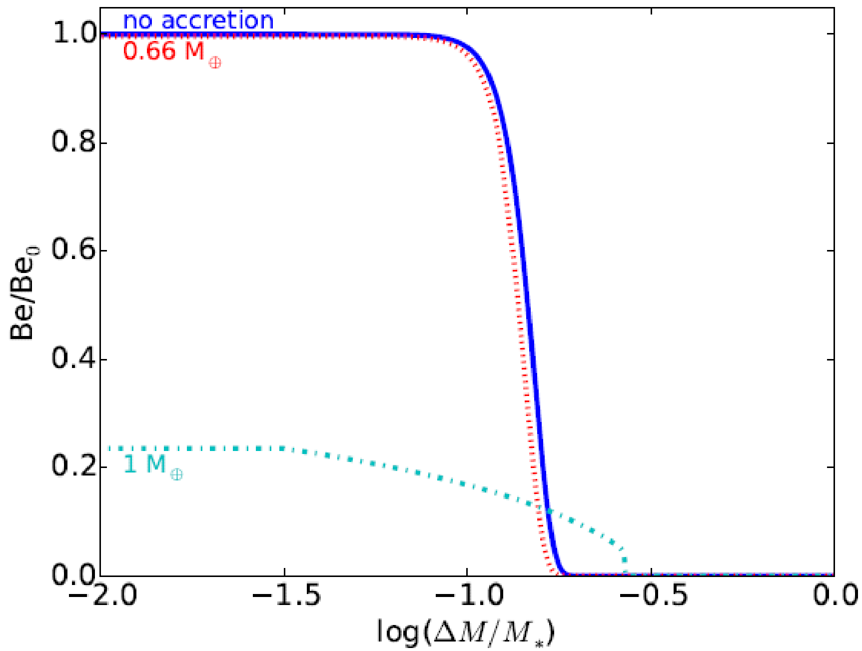


lithium and beryllium destruction induced by fingering convection

lithium (left)

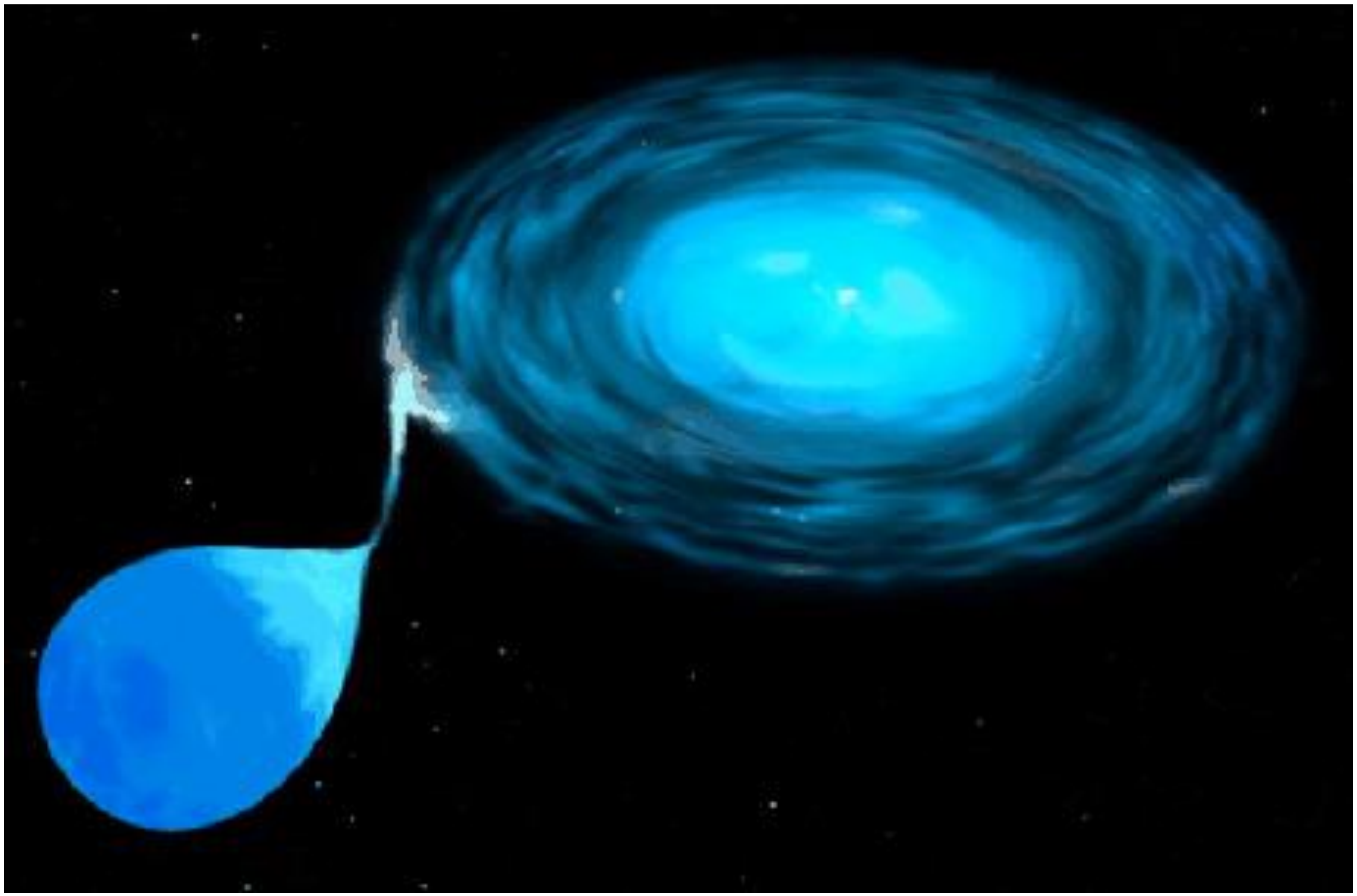


beryllium (right)



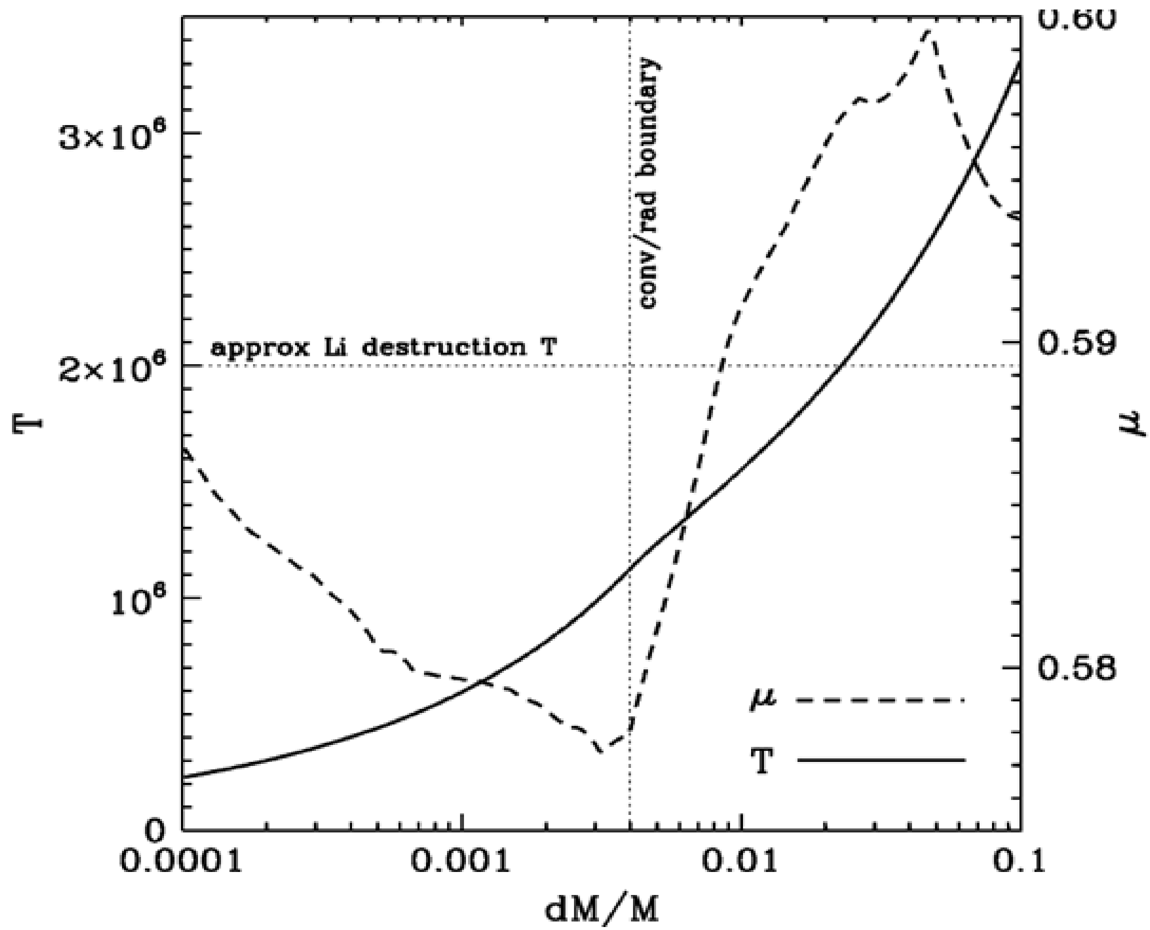
Outline

- Computations of atomic diffusion in stellar interiors:
    - include radiative accelerations
    - important results
- Fingering convection:
    - the physical process and 3D numerical simulations
    - consequences of atomic diffusion in MS stars
    - consequences of planetary matter accretion
    - the case of CEMP stars
    - Debris disks around white dwarfs : the fate of planetary systems



Carbon Enhanced Metal Poor Stars

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



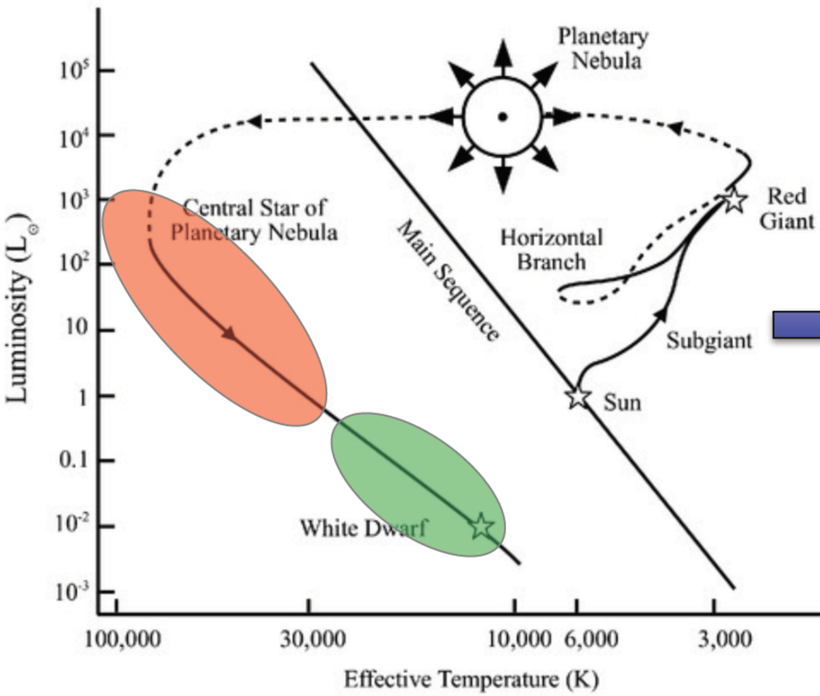
Thompson et al. 2008

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

Outline

- Computations of atomic diffusion in stellar interiors:
  - include radiative accelerations
  - important results
- Fingering convection:
  - the physical process and 3D numerical simulations
  - consequences of atomic diffusion in MS stars
  - consequences of planetary matter accretion
  - the case of CEMP stars
  - Debris disks around white dwarfs : the fate of planetary systems

What happens to planetary systems once their host stars evolve?



- **planet ejections or collisions** (Debes & Sigurdsson 2002, Veras et al. 2011; Voyatzis et al. 2013)
- **smaller bodies are likely to be scattered** (Bonsor et al. 2011, Debes et al. 2012)
- **a fraction of planets can survive**

Sackman et al. 1993; Duncan & Lissauer 1998 (solar system)

Villaver & Livio 2007, 2009; Nordhaus et al. 2010, Mustill & Villaver 2012 (general planetary systems)

An important fraction of observed white dwarfs (DAZ and DBZ) suffer accretion from debris disks

- lines of heavy elements are observed :

  in DAZ with T_{eff} between 6000 K and 27000 K

  in DBZ with T_{eff} between 13500 K and 21000 K

(e.g. Desharnais et al. 2008, Zuckerman et al. 2010 and 2011, Koester et al. 2014, Rochetto et al 2015…)

- The heavy elements abundances have ratios similar to terrestrial planets

  (e.g. for C, Si, O, Mg, S, Ti, Cr, Mn, Fe).

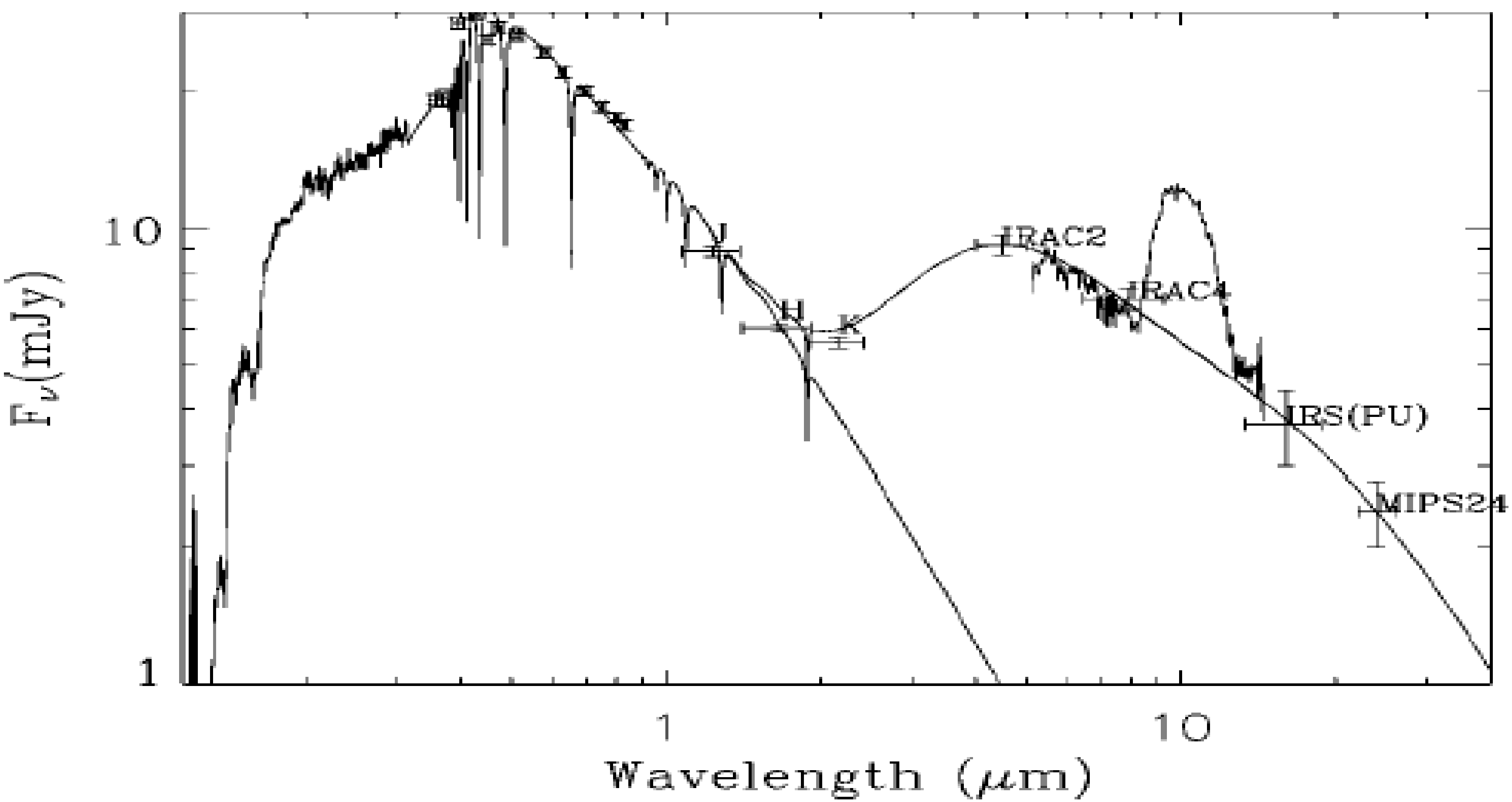
(e.g. Melis et al. 2011, Dufour et al. 2012, Gänsicke et al. 2011, Xu et al. 2014…)

- Infrared excess:

  First discovered around the ZZ Ceti G29-38 (Zuckerman & Becklin, 1987)

  Spitzer + ground based IR telescopes find IR excess in many WDs

  Wide range of Teff



Spectral Energy Distribution (SED) of G29-38 (*Reach et al. 2005, ApJ, 635, L161)*

UV: IUE ; Palomar optical spectrophotometry; 2MASS J-H-K photometry;

Spitzer: IRAC: Infrared Array Camera; MIPS: Multiband Imaging Photometer; IRS: Infrared Spectrograph

Ly_α $Ly_{\beta,}$ Balmer and Paschen series, 9-11 µm features: silicates

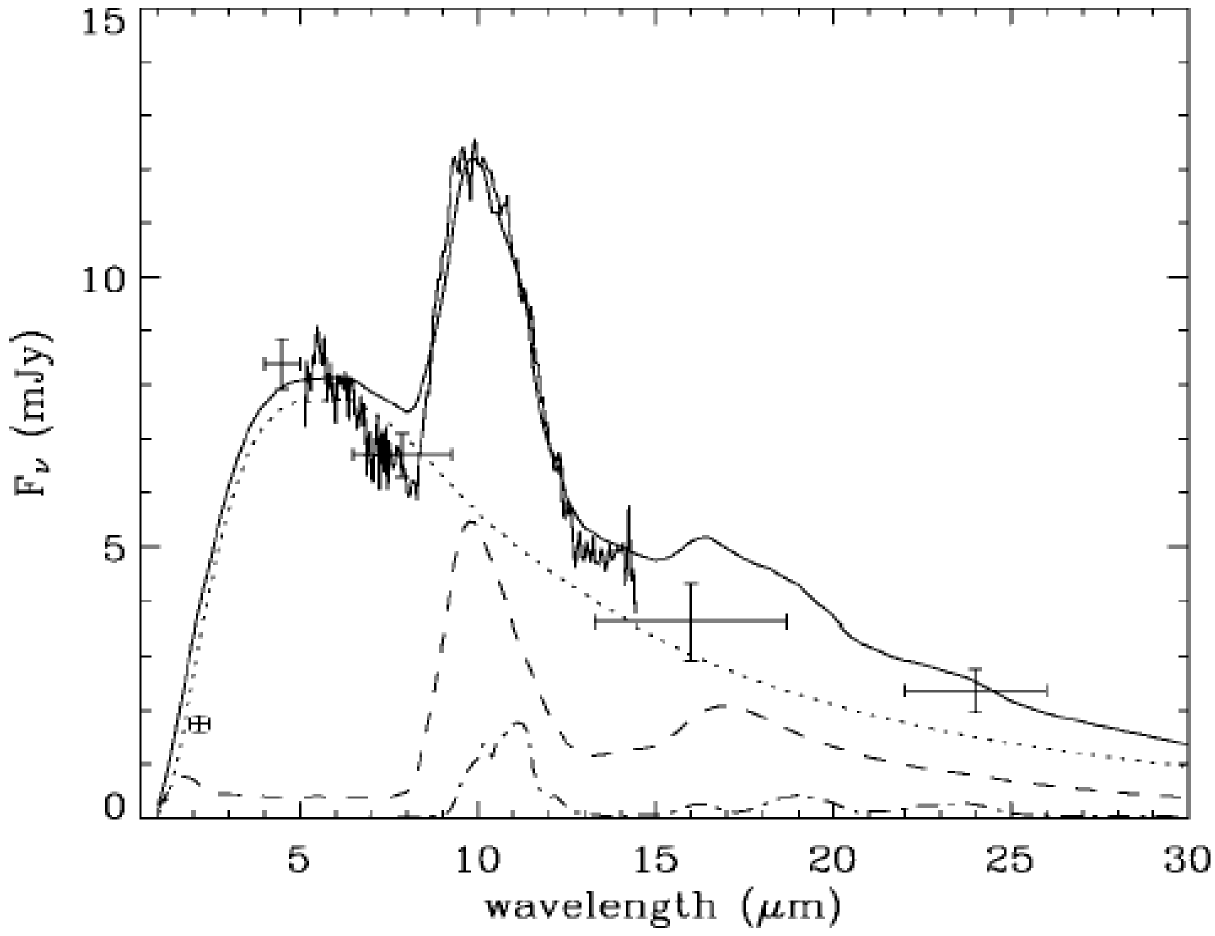
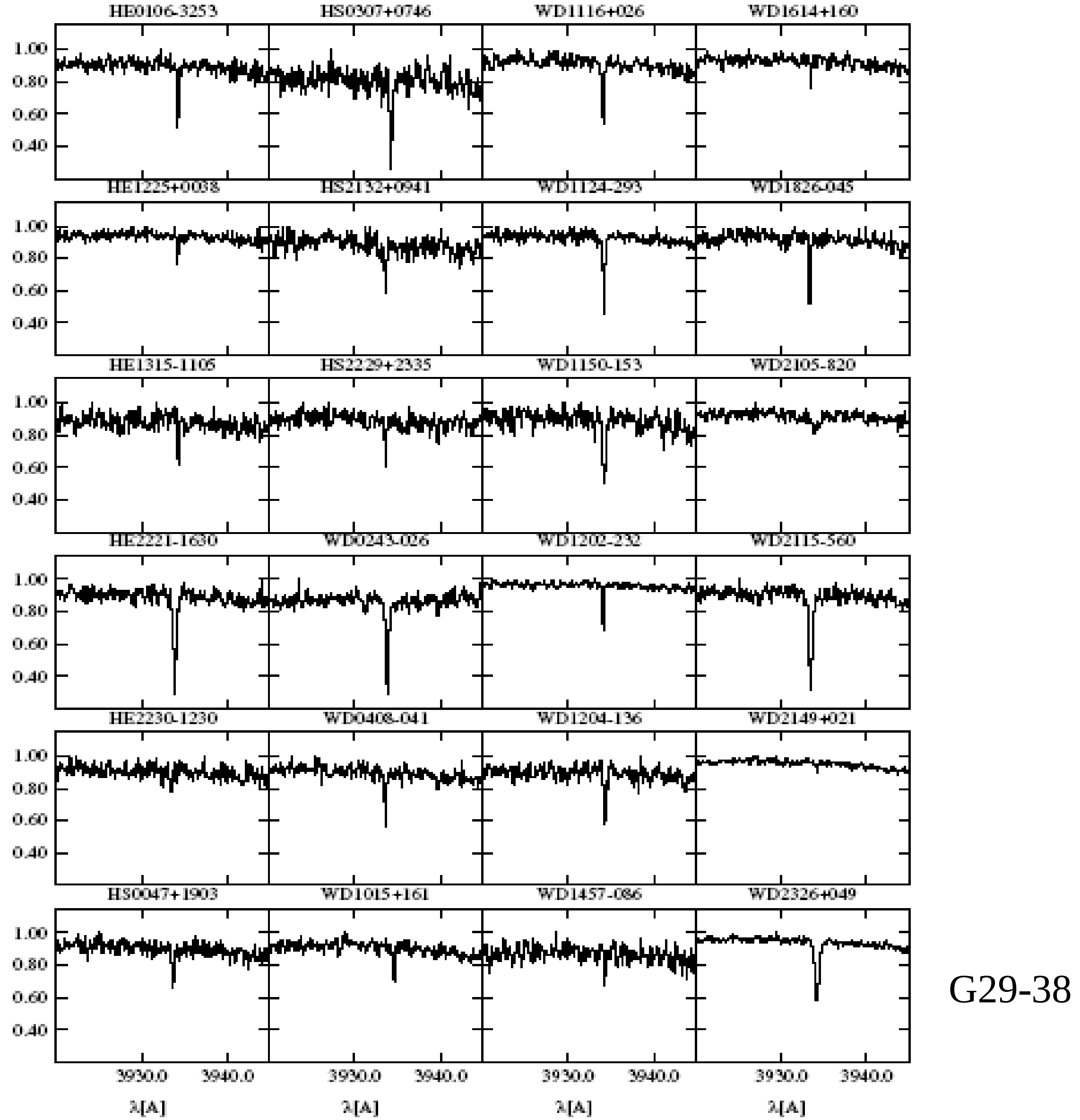


FIG. 3.—Infrared excess of G29-38 compared to the best-fit model (*solid line*), consisting of three compositions: amorphous carbon (*dotted line*), amorphous olivine (*long-dashed line*), and forsterite (*dot-dashed line*).

Dust grain abundance ratio (by number): olivine:carbon:forsterite = 5:12:2

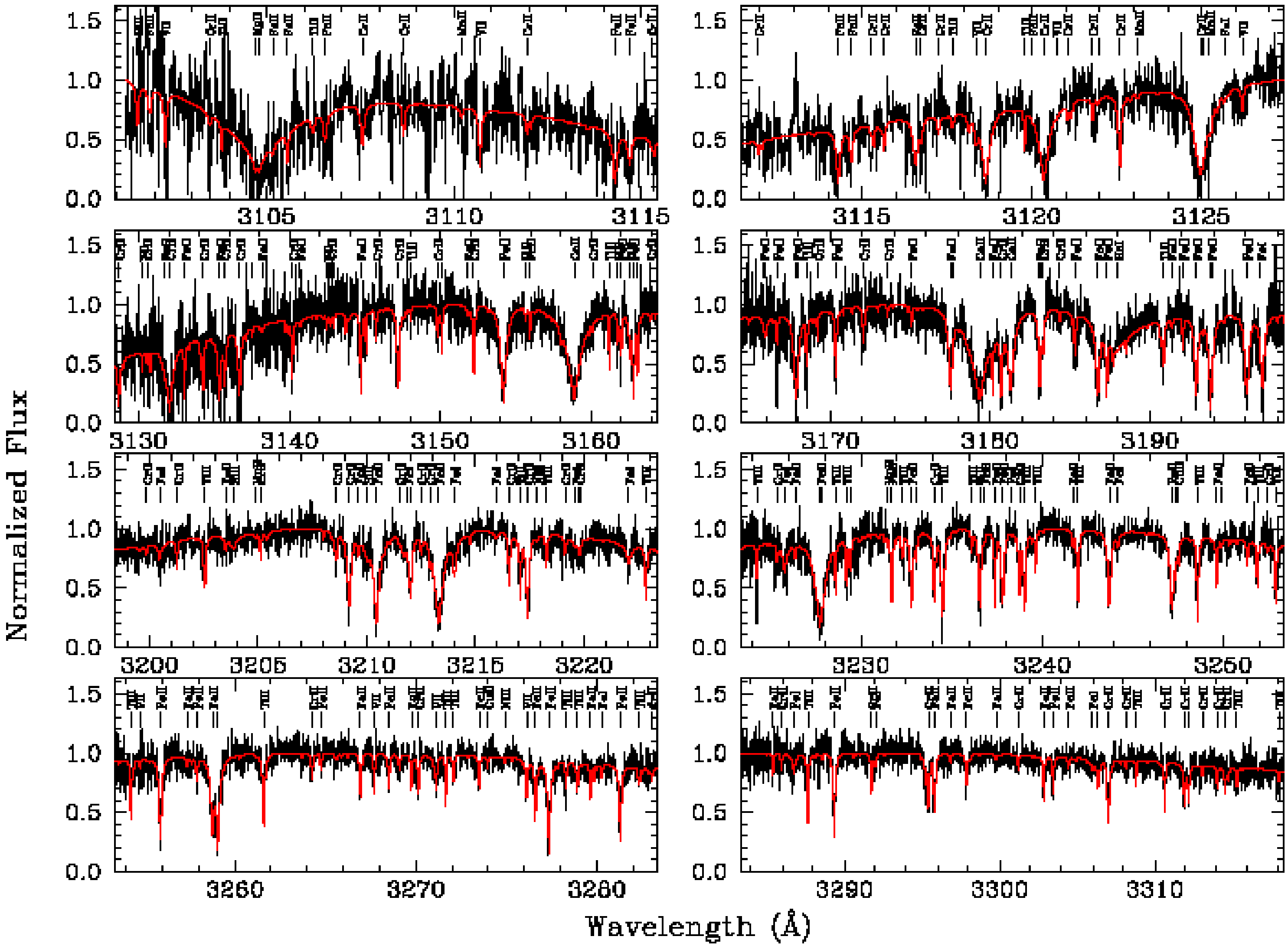
olivine: $(Mg,Fe)_2[SiO_4]$; forsterite: Mg_2SiO_4

Reach et al. 2005, ApJ, 635, L161



Ca in DAZ white dwarfs *(Koester et al. 2005, A&A, 432, 1025)*

6800 K < T_{eff} <20400 K



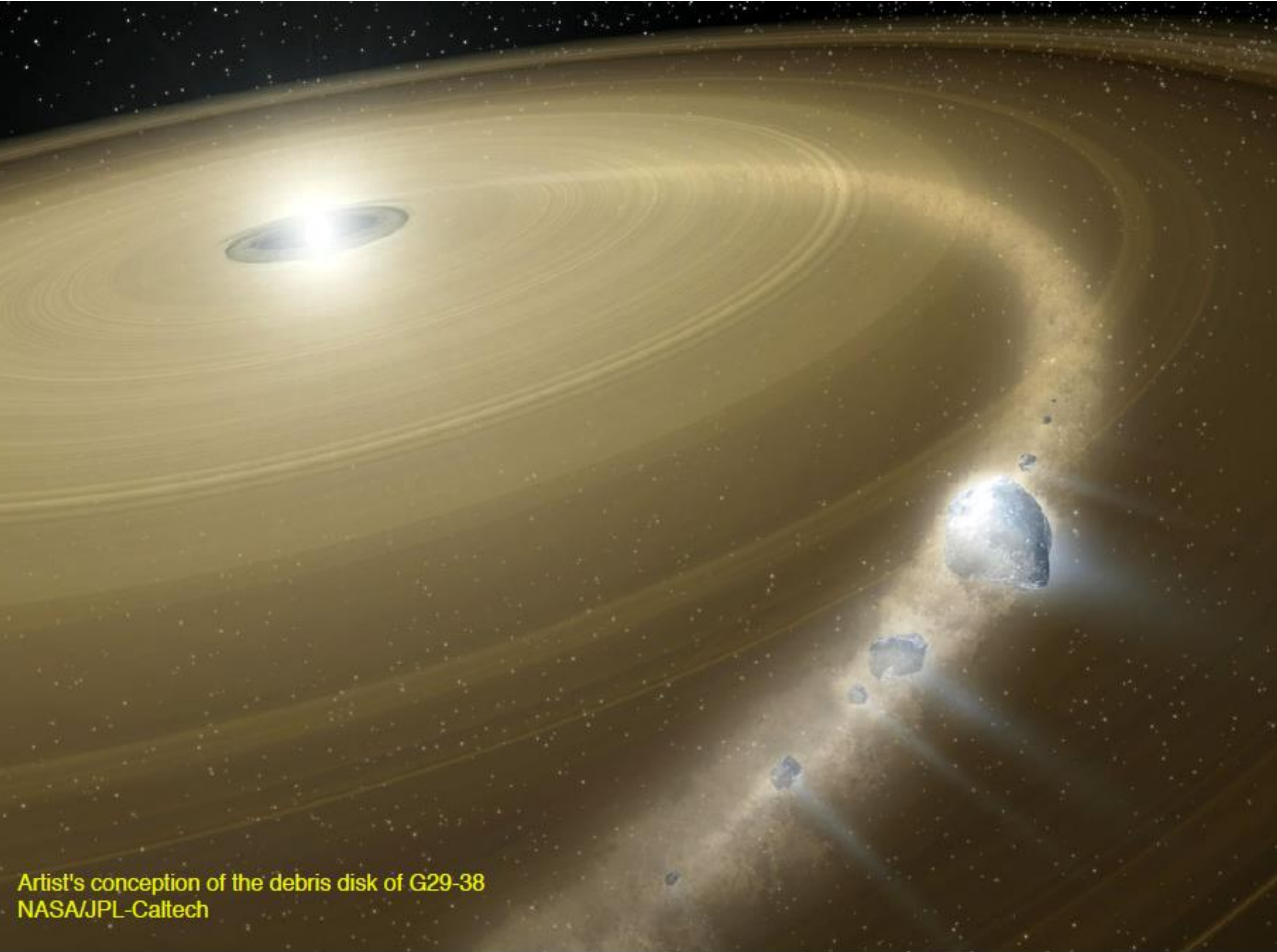
A fraction of the HIRES spectrum of J0738+1835 (*Dufour et al. 2012, ApJ, 749, 6)*

Table 2

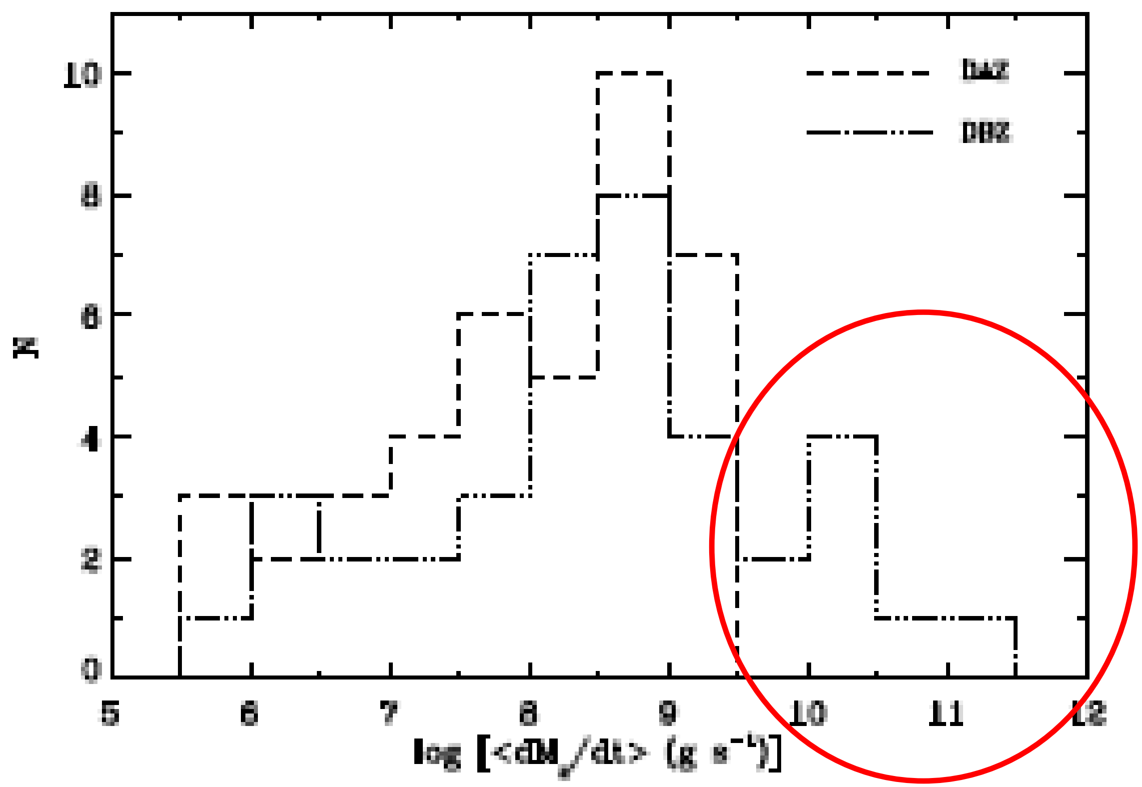
J0738+1835 Metal Pollution

Element	log $[n(\mathrm{Z})/n(\mathrm{He})]_{\mathrm{phot}}$	$M_{\mathrm{CVZ}}/(10^{21}$ g)	log τ_{set} (yr) (yr)	$[n(\mathrm{Z})/n(\mathrm{Fe})]_{\mathrm{acc}}$	$\dot{M}/(10^{8}\ \mathrm{g\ s^{-1}})$
1 H	-5.73 ± 0.17	0.310	∞	...	...
8 O	-3.81 ± 0.19	407.86	5.244	9.52	740.2
11 Na	-6.36 ± 0.16	1.639	5.238	2.7×10^{-2}	3.02
12 Mg	-4.68 ± 0.07	83.33	5.258	1.24	146.38
13 Al	-6.39 ± 0.11	1.792	5.244	2.5×10^{-2}	3.25
14 Si	-4.90 ± 0.16	57.99	5.248	0.77	104.36
20 Ca	-6.23 ± 0.15	3.907	5.044	5.8×10^{-2}	11.24
21 Sc	-9.55 ± 0.18	2.05×10^{-3}	5.010	2.9×10^{-5}	6.38×10^{-3}
22 Ti	-7.95 ± 0.11	8.87×10^{-2}	5.007	1.2×10^{-3}	0.278
23 V	-8.50 ± 0.17	2.65×10^{-2}	5.006	3.4×10^{-4}	8.31×10^{-2}
24 Cr	-6.76 ± 0.12	1.492	5.026	1.8×10^{-2}	4.48
25 Mn	-7.11 ± 0.11	0.693	5.028	7.7×10^{-3}	2.07
26 Fe	-4.98 ± 0.09	94.91	5.047	1.00	271.32
27 Co	-7.76 ± 0.19	0.165	5.042	1.7×10^{-3}	0.479
28 Ni	-6.31 ± 0.10	4.721	5.063	4.6×10^{-2}	12.997
Total		658.95			1301.7

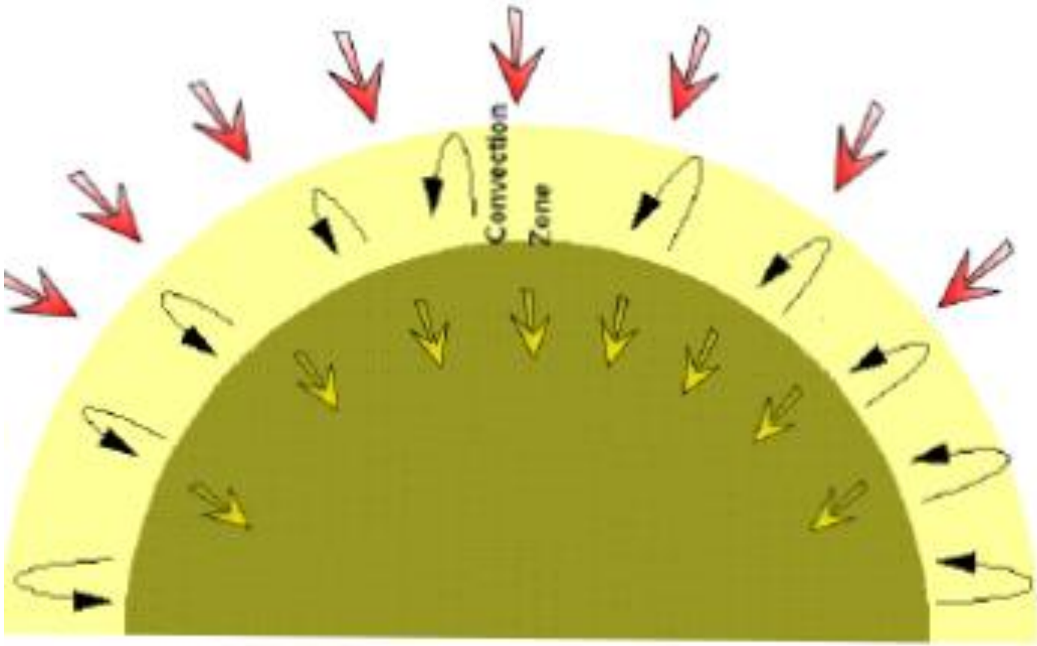
Dufour et al 2012, ApJ, 749, 6



Artist's conception of the debris disk of G29-38
NASA/JPL-Caltech



Farihi et al. MNRAS 424, 464, 2012



Importance of fingering convection

different in DA (hydrogen) and DB (helium) WD

(Deal et al. 2013)

Examples of accretion rates needed to explain the observed abundances without or with fingering convection included (Deal et al. 2013)

Model	Teff	log (dM/dt) (no fingering)	log (dM/dt) (fingering)
DAZ	10600 K	9.23	9.83
DAZ	16900 K	7.70	9.40
DBZ	10600 K	8.04	8.04
DBZ	17100 K	10.08	10.08

Fingering convection is less efficient in DBs than in DAs because

1) The convection zone is deeper and the Lewis number smaller
2) The initial mu value is larger

conclusions

- Importance of taking into account complete atomic diffusion in the computations of stellar interiors

- Importance of the fingering mixing induced by local element accumulation

- In case of accretion of « heavy matter » onto the star, importance of the induced fingering convection:
  - The accreted metals do not stay in the outer convective zone, except in case of continuous accretion and steady state
  - The induced mixing can lead to lithium (and possibly beryllium) depletion

- Tests: 3D numerical simulations, asteroseismology

- Consequences: determination of stellar parameters (e.g. ages) chemical evolution of galaxies, etc….