Du nouveau dans les étoiles...

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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 $\mu$-gradients
  (leads to extra mixing in various cases)
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:
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  • important results

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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
Treatment of collisions (Boltzmann integro-differential equation):

\[ f(c+Fdt, r+cdt, t+dt) - f(c, r, t) \] = (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 \(t\)

\[
\left(\frac{\partial f_i}{\partial t}\right)_{\text{col}} = \iiint (f'_i f'_j - f_i f_j) \, v \, b \, db \, d\epsilon \, dc_j
\]

Maxwellian \( \left(\frac{\partial f_i}{\partial t}\right)_{\text{col}} = 0 \) : \( f'_i f'_j = f_i f_j \)

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

Compute the collision integrals as a development in terms of small knudsen number \( k = l/L = t_{mic}/t_{mac} \)
derived equations:

**Diffusion equation:**
\[
\frac{\partial (\rho c_i)}{\partial t} + \text{div}(\rho c_i v_i) = 0
\]

for test atoms:
(including mixing coefficient \(D_{th}\))

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

**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:
\[
D = \frac{1}{3} l C_M = \frac{1}{3} t_{col} C_M^2 = t_{col} \frac{kT}{m}
\]

\[
\rightarrow \quad v_d = t_{col} g_{\text{eff}}
\]
Burgers diffusion equations

\[
\frac{dp_i}{dr} + \rho_i (g - g_{rad,i}) - n_i \bar{Z}_i eE = \sum_{j \neq i}^N K_{ij} (w_j - w_i) - \sum_{j \neq i}^N K_{ij} z_{ij} \frac{m_j r_i - m_i r_j}{m_i + m_j},
\]

including the heat flow equations,

\[
\frac{5}{2} n_i k_B \nabla T = \frac{5}{2} \sum_{j \neq i}^N z_{ij} \frac{m_j}{m_i + m_j} (w_j - w_i) - \frac{2}{5} K_{ii} z_{ii}' r_i - \sum_{j \neq i}^N \frac{K_{ij}}{(m_i + m_j)^2} (3m_i^2 + m_j^2 z_{ij}' + 0.8m_i m_j z_{ij}'' ) r_i + \sum_{j \neq i}^N \frac{K_{ij} m_i m_j}{(m_i + m_j)^2} (3 + z_{ij}' - 0.8z_{ij}'' ) r_j.
\]

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:

\[ g_{i,n} = \frac{1}{m_2 N_2} \frac{4\pi}{3c} \left( -\frac{\partial T}{\partial r} \right) \left[ \frac{\partial B_v}{\partial T} \right] \left[ \int_{-\infty}^{+\infty} \frac{N_{i,n} \frac{\pi e^2}{m_e c} f_{n,m} g(v) dv}{\chi_v(R) \rho + N_{i,n} \frac{\pi e^2}{m_e c} f_{n,m} g(v)} \right] \]

unsaturated line

\[ g_{\text{rad}} \text{ independent of } N \]

saturated line

\[ g_{\text{rad}} \uparrow \text{ when } N \downarrow \]
Montreal-Montpellier code:
Complete computations of radiative accelerations using OPAL detailed opacity computations

TGEC code:
Approximate computations using SVP (sing-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: 3M_{\odot}, 70\text{Myr} (Richer et al. 1999)

Possible macroscopic consequences of atomic diffusion: (other than observed abundances)
- dynamical convection
- thermohaline convection
- stellar oscillations
**Mic-mac connection:**

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:** $g_e = g - g_R \approx g$

BUT!
The accumulation of the element and the collisions with the surroundings lead to an increase of $\mu$

... and to an increase of the local opacity!!!
Fig. 8.—Convection and semiconvection zones in three models with turbulence parameterized by 3D noise: (a) 1.5 $M_{\odot}$, (b) 1.7 $M_{\odot}$, and (c) 2.1 $M_{\odot}$. The radiative zones are in white, the convection zones in black, and the semiconvection zones in gray. The convection zones $a$ and $b$, due to $\alpha$ and $\beta$, rapidly disappear because of He settling. The convection zone $c$ is the Fe convection zone. Close to the central convective core, there appear semiconvection zones, $a$ and $d$. 

Richard, Michaud, Richer 2001
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• *Computations of atomic diffusion in stellar interiors:*
  • include radiative accelerations
  • important results

• *Fingering convection:*
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  • consequences of atomic diffusion in MS stars
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  • 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:
\[ \alpha = \frac{1}{\rho} (\partial \rho / \partial T)_{S,P} \]
\[ \beta = \frac{1}{\rho} (\partial \rho / \partial S)_{T,P} \]

and the lewis number:
\[ \tau = \kappa_S / \kappa_T = t_T / t_S \]

Salt fingers can grow if:
\[ 1 \leq R_\rho \leq \tau^{-1} \]

Double-diffusion experiment (Pringle et al. 2002)

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

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

\[ \nabla_{\mu} = \frac{d\ln \mu}{d\ln P} \text{ plays the role of the salinity gradient;} \]

\[ \nabla_{\text{rad}} - \nabla \text{ plays the role of the temperature gradient} \]

« fingers » form if :

\[ 1 < R_0 < \frac{1}{\tau} \]

with:

\[ R_0 = \frac{\nabla_{ad} - \nabla_{\text{rad}}}{\nabla_{\mu}} \]

and

\[ \tau = \frac{\kappa_{\mu}}{\kappa_T} = \frac{\tau_T}{\tau_\mu} \]

For \( R_0 < 1 \), dynamical convection

For \( R_0 = 1/\tau \), dissipation

Simulations by Brown et al. 2013

\( R_0 = 3 \); \( \text{Pr} = 1/10; \tau = 1/30 \)

reduced time: \( t=100 \) (prior to saturation)

155 (disrupted modes), 180 (saturated regime)
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Théado, Vauclair, Alecian, Leblanc, 2009

$1.7 \ M_\odot$

$\log \kappa$

$\mu$

$(\nabla_{\text{rad}} - \nabla_{\text{ad}})$
Deal et al, in prep. 1.7M\textsubscript{Sun}
Disconnected fingering convection zones

Connected fingering convection zones

Deal et al, in prep. 1.7Msun
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heavy elements in EHS: original abundances.

Data Israeli

Israelian et al, Nature 2010 (contestation: Melendez et al.)
<table>
<thead>
<tr>
<th></th>
<th>16 Cygni A</th>
<th>16 Cygni B</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{\text{eff}}$ (K)</td>
<td>$5825 \pm 50^a$</td>
<td>$5750 \pm 50^a$</td>
</tr>
<tr>
<td></td>
<td>$5813 \pm 18^b$</td>
<td>$5749 \pm 17^b$</td>
</tr>
<tr>
<td></td>
<td>$5796 \pm 34^c$</td>
<td>$5753 \pm 30^c$</td>
</tr>
<tr>
<td></td>
<td>$5839 \pm 42^d$</td>
<td>$5809 \pm 39^d$</td>
</tr>
<tr>
<td></td>
<td>$5830 \pm 7^f$</td>
<td>$5751 \pm 6^f$</td>
</tr>
<tr>
<td>log g</td>
<td>$4.33 \pm 0.07^a$</td>
<td>$4.34 \pm 0.07^a$</td>
</tr>
<tr>
<td></td>
<td>$4.282 \pm 0.017^b$</td>
<td>$4.328 \pm 0.017^b$</td>
</tr>
<tr>
<td></td>
<td>$4.38 \pm 0.12^c$</td>
<td>$4.40 \pm 0.12^c$</td>
</tr>
<tr>
<td></td>
<td>$4.30 \pm 0.02^f$</td>
<td>$4.35 \pm 0.02^f$</td>
</tr>
<tr>
<td>[Fe/H]</td>
<td>$0.096 \pm 0.026^a$</td>
<td>$0.052 \pm 0.021^a$</td>
</tr>
<tr>
<td></td>
<td>$0.104 \pm 0.012^b$</td>
<td>$0.061 \pm 0.011^b$</td>
</tr>
<tr>
<td></td>
<td>$0.07 \pm 0.05^c$</td>
<td>$0.05 \pm 0.05^c$</td>
</tr>
<tr>
<td></td>
<td>$0.101 \pm 0.008^f$</td>
<td>$0.054 \pm 0.008^f$</td>
</tr>
<tr>
<td>A(Li)</td>
<td>$1.27 \pm 0.05^i$</td>
<td>$\leq 0.6^i$</td>
</tr>
<tr>
<td>A(Be)</td>
<td>$0.99 \pm 0.08^j$</td>
<td>$1.06 \pm 0.08^j$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>16 Cygni A</td>
<td>16 Cygni B</td>
</tr>
<tr>
<td>Mass ($M_\odot$)</td>
<td>$1.05 \pm 0.02^b$</td>
<td>$1.00 \pm 0.01^b$</td>
</tr>
<tr>
<td></td>
<td>$1.07 \pm 0.05^d$</td>
<td>$1.05 \pm 0.04^d$</td>
</tr>
<tr>
<td></td>
<td>$1.11 \pm 0.02^g$</td>
<td>$1.07 \pm 0.02^g$</td>
</tr>
<tr>
<td>Radius ($R_\odot$)</td>
<td>$1.218 \pm 0.012^d$</td>
<td>$1.098 \pm 0.010^d$</td>
</tr>
<tr>
<td></td>
<td>$1.22 \pm 0.02^c$</td>
<td>$1.12 \pm 0.02^c$</td>
</tr>
<tr>
<td></td>
<td>$1.243 \pm 0.008^g$</td>
<td>$1.127 \pm 0.007^g$</td>
</tr>
<tr>
<td>Luminosity ($L_\odot$)</td>
<td>$1.56 \pm 0.05^g$</td>
<td>$1.27 \pm 0.04^g$</td>
</tr>
<tr>
<td>Age (Gyrs)</td>
<td>$7.15^{+0.04}_{-1.03}^b$</td>
<td>$7.26^{+0.69}_{-0.33}^b$</td>
</tr>
<tr>
<td></td>
<td>$6.9 \pm 0.03^g$</td>
<td>$6.7 \pm 0.03^g$</td>
</tr>
<tr>
<td>$Z_i$</td>
<td>$0.024 \pm 0.002^g$</td>
<td>$0.023 \pm 0.002^g$</td>
</tr>
<tr>
<td>$Y_i$</td>
<td>$0.25 \pm 0.01^g$</td>
<td>$0.25 \pm 0.01^g$</td>
</tr>
<tr>
<td>$v \sin i$ (km.s$^{-1}$)</td>
<td>$2.23 \pm 0.07^h$</td>
<td>$1.27 \pm 0.04^h$</td>
</tr>
<tr>
<td>$P_{\text{rot}}$ (days)</td>
<td>$23.8^{+1.5}_{-1.8}^h$</td>
<td>$23.2^{+11.5}_{-3.2}^h$</td>
</tr>
<tr>
<td>Planet detected</td>
<td>no</td>
<td>yes$^k$</td>
</tr>
</tbody>
</table>
Metal-rich accretion and thermohaline instabilities in exoplanets-host stars: consequences on the light elements abundances

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![Graphs showing 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.](image)
Seismic studies

16 Cyg A (left)  
16 Cyg B (right)
lithium and beryllium destruction induced by fingering convection

lithium (left)  beryllium (right)

![Graphs showing lithium and beryllium destruction](image)
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Accretion Disk

Binary System

Credit: NASA, HST, artist's Visualization

Accretion from a companion, e.g., CEMP
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.
Computations of atomic diffusion in stellar interiors:
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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 $T_{\text{eff}}$ between 6000 K and 27000 K
  - in DBZ with $T_{\text{eff}}$ 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

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

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

Ly$_\alpha$, Ly$_\beta$, Balmer and Paschen series, 9-11 µm features: silicates
Dust grain abundance ratio (by number): olivine:carbon:forsterite = 5:12:2

olivine: (Mg,Fe)$_2$SiO$_4$ ; forsterite: Mg$_2$SiO$_4$


$6800 \text{ K} < T_{\text{eff}} < 20400 \text{ K}$
<table>
<thead>
<tr>
<th>Element</th>
<th>log ([n(Z)/n(He)]_{\text{phot}})</th>
<th>(M_{\text{CVZ}}/(10^{21} \text{ g}))</th>
<th>log (\tau_{\text{set}} (\text{yr}))</th>
<th>([n(Z)/n(\text{Fe})]_{\text{acc}})</th>
<th>(\dot{M}/(10^8 \text{ g s}^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 H</td>
<td>(-5.73 \pm 0.17)</td>
<td>0.310</td>
<td>(\infty)</td>
<td>(\ldots)</td>
<td>(\ldots)</td>
</tr>
<tr>
<td>8 O</td>
<td>(-3.81 \pm 0.19)</td>
<td>407.86</td>
<td>5.244</td>
<td>9.52</td>
<td>740.2</td>
</tr>
<tr>
<td>11 Na</td>
<td>(-6.36 \pm 0.16)</td>
<td>1.639</td>
<td>5.238</td>
<td>(2.7 \times 10^{-2})</td>
<td>3.02</td>
</tr>
<tr>
<td>12 Mg</td>
<td>(-4.68 \pm 0.07)</td>
<td>83.33</td>
<td>5.258</td>
<td>(1.24)</td>
<td>146.38</td>
</tr>
<tr>
<td>13 Al</td>
<td>(-6.39 \pm 0.11)</td>
<td>1.792</td>
<td>5.244</td>
<td>(2.5 \times 10^{-2})</td>
<td>3.25</td>
</tr>
<tr>
<td>14 Si</td>
<td>(-4.90 \pm 0.16)</td>
<td>57.99</td>
<td>5.248</td>
<td>(0.77)</td>
<td>104.36</td>
</tr>
<tr>
<td>20 Ca</td>
<td>(-6.23 \pm 0.15)</td>
<td>3.907</td>
<td>5.044</td>
<td>(5.8 \times 10^{-2})</td>
<td>11.24</td>
</tr>
<tr>
<td>21 Sc</td>
<td>(-9.55 \pm 0.18)</td>
<td>(2.05 \times 10^{-3})</td>
<td>5.010</td>
<td>(2.9 \times 10^{-5})</td>
<td>(6.38 \times 10^{-3})</td>
</tr>
<tr>
<td>22 Ti</td>
<td>(-7.95 \pm 0.11)</td>
<td>(8.87 \times 10^{-2})</td>
<td>5.007</td>
<td>(1.2 \times 10^{-3})</td>
<td>0.278</td>
</tr>
<tr>
<td>23 V</td>
<td>(-8.50 \pm 0.17)</td>
<td>(2.65 \times 10^{-2})</td>
<td>5.006</td>
<td>(3.4 \times 10^{-4})</td>
<td>(8.31 \times 10^{-2})</td>
</tr>
<tr>
<td>24 Cr</td>
<td>(-6.76 \pm 0.12)</td>
<td>1.492</td>
<td>5.026</td>
<td>(1.8 \times 10^{-2})</td>
<td>4.48</td>
</tr>
<tr>
<td>25 Mn</td>
<td>(-7.11 \pm 0.11)</td>
<td>0.693</td>
<td>5.028</td>
<td>(7.7 \times 10^{-3})</td>
<td>2.07</td>
</tr>
<tr>
<td>26 Fe</td>
<td>(-4.98 \pm 0.09)</td>
<td>94.91</td>
<td>5.047</td>
<td>(1.00)</td>
<td>271.32</td>
</tr>
<tr>
<td>27 Co</td>
<td>(-7.76 \pm 0.19)</td>
<td>0.165</td>
<td>5.042</td>
<td>(1.7 \times 10^{-3})</td>
<td>0.479</td>
</tr>
<tr>
<td>28 Ni</td>
<td>(-6.31 \pm 0.10)</td>
<td>4.721</td>
<td>5.063</td>
<td>(4.6 \times 10^{-2})</td>
<td>12.997</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>658.95</td>
<td></td>
<td></td>
<td>1301.7</td>
</tr>
</tbody>
</table>

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)

<table>
<thead>
<tr>
<th>Model</th>
<th>Teff</th>
<th>log (dM/dt) (no fingering)</th>
<th>log (dM/dt) (fingering)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DAZ</td>
<td>10600 K</td>
<td>9.23</td>
<td>9.83</td>
</tr>
<tr>
<td>DAZ</td>
<td>16900 K</td>
<td>7.70</td>
<td>9.40</td>
</tr>
<tr>
<td>DBZ</td>
<td>10600 K</td>
<td>8.04</td>
<td>8.04</td>
</tr>
<tr>
<td>DBZ</td>
<td>17100 K</td>
<td>10.08</td>
<td>10.08</td>
</tr>
</tbody>
</table>

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....