Diffusion and its manifestation in stellar atmospheres

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Diffusion separation of chemical elements under competition of radiative levitation and gravitational settling

Was first considered in details by G. Michaud (1970) to explain chemical anomalies observed in the atmospheres of Ap stars. Theoretical study of stratification results in calculations of self-consistent diffusion models based on different model atmosphere codes (Phoenix and some others). Stratifications of up to 29 chemical elements were calculated and included in atmospheric modelling.

Hui-Bon-Hoa et al. (2000); LeBlanc et al. (2010) – blue horizontal-branch (BHB) stars

LeBlanc (2003, 2005); LeBlanc, Monin, Hui-Bon-Hoa, & Hauschild (2009) – Ap stars

Stift & Alecian (2010, 2012) – Ap stars

Main diffusion equations

$$g_{\rm rad}(A) = \frac{4\pi}{c}\frac{1}{X_A}\int_0^\infty \kappa_\lambda(A) H_\lambda \mathrm{d}\lambda$$

- radiative acceleration, X_A – mass fraction

$$V_i = D_i\left\{-\frac{\partial \ln c_i}{\partial r} + \frac{m_i}{kT}\left[g^i_{\rm rad} - \left(\frac{2A_i - Z_i - 1}{2A_i}\right) g\right] + (3.45 Z_i^2 - 0.82)\frac{\partial \ln T}{\partial r}\right\}$$

m_i, A_i, Z_i – mass, atomic mass and the charge,

g – local gravitational acceleration,

g^i_{rad} – the radiative acceleration,

D_i – diffusion coefficient

Effective acceleration is expressed as

$$g^i_{\rm eff} = g^i_{\rm rad} - \left(\frac{2A_i - Z_i - 1}{2A_i}\right) g$$

In stellar atmosphere element is in few ionization stages, therefore the total radiative acceleration is a weighted mean of different ions:

$$g_{\rm rad} = \frac{\sum_i N_i D_i \, g^i_{\rm rad}}{\sum_i N_i D_i}.$$

The competion between radiative acceleration and gravity produces element separation in quite stellar atmospheres

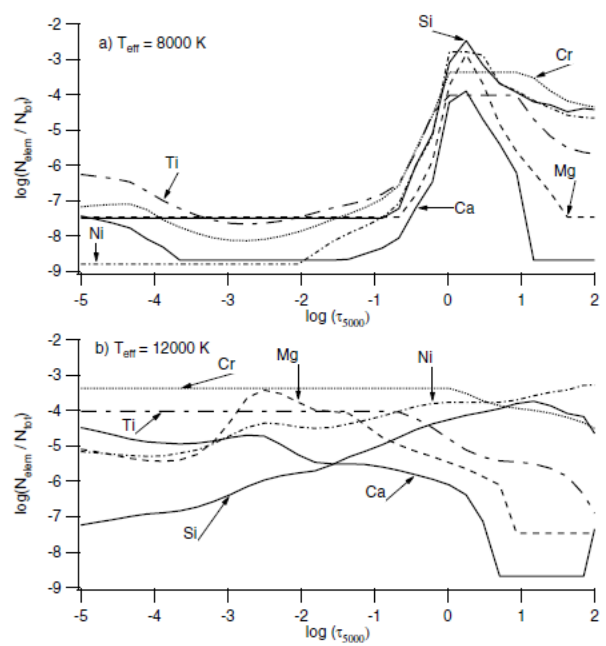
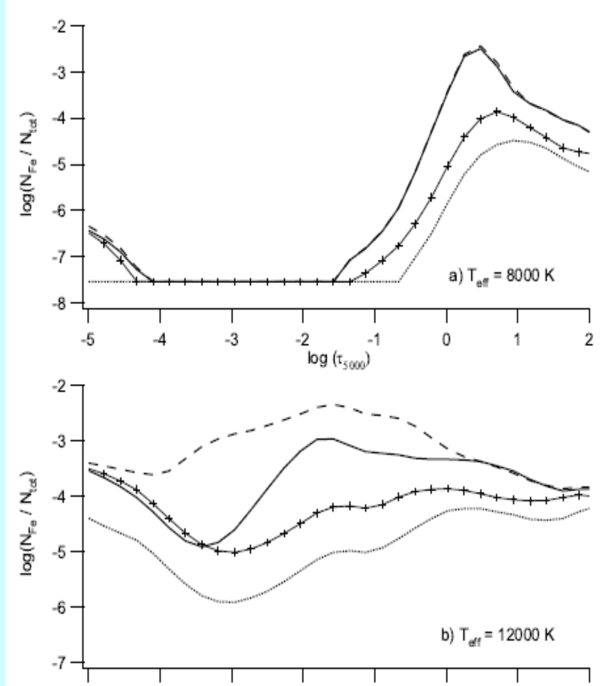


Fig. 9. The abundance of the elements Mg, Si, Ca, Ti, Cr and Ni as a function of optical depth for models with a) $T_{\rm eff}$ = 8000 K and b) $T_{\rm eff}$ = 12 000 K (both for $\log g$ = 4.0) assuming the Montmerle & Michaud (1976) redistribution.



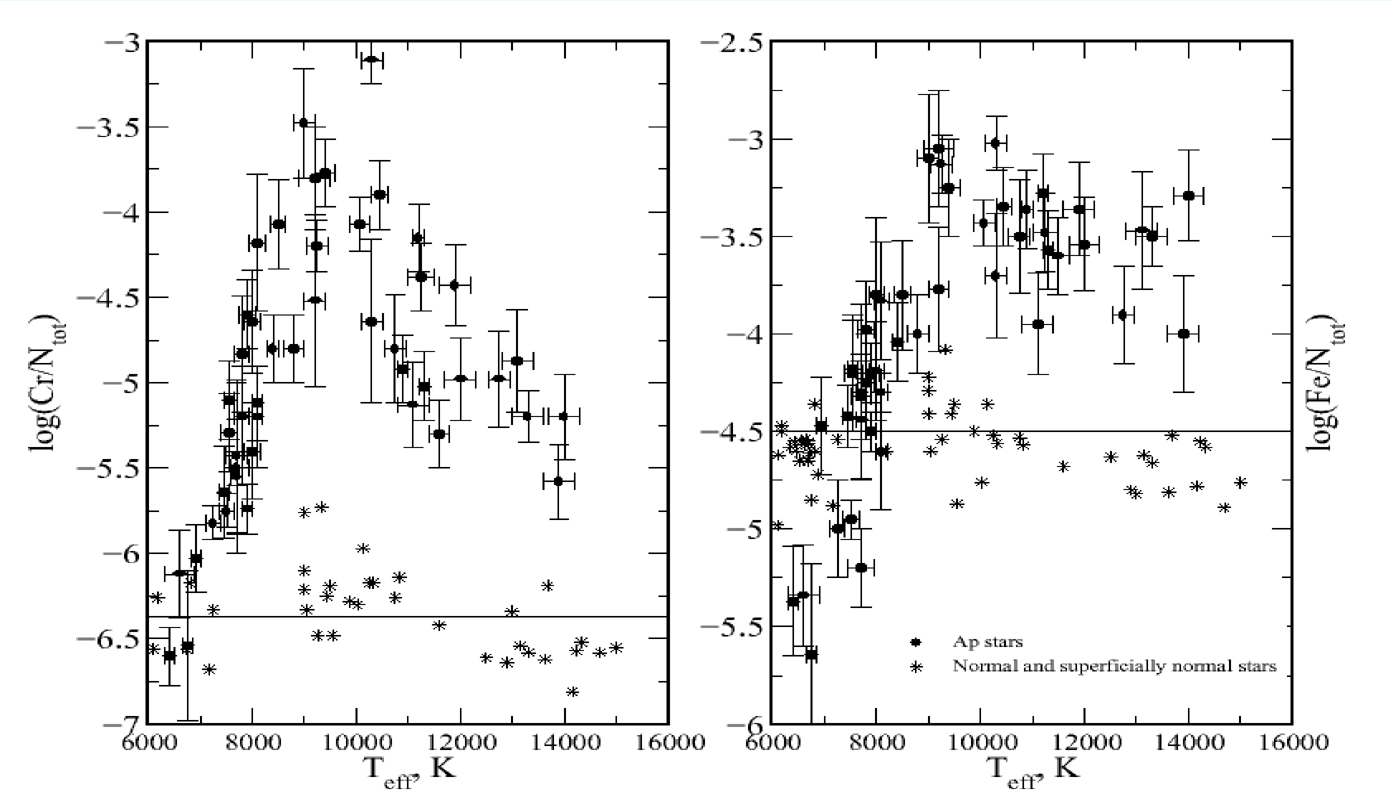
Fe distribution

LeBlanc et al. 2009, A&A 495, 937

How element stratification manifests itself in stellar stmospheres ?

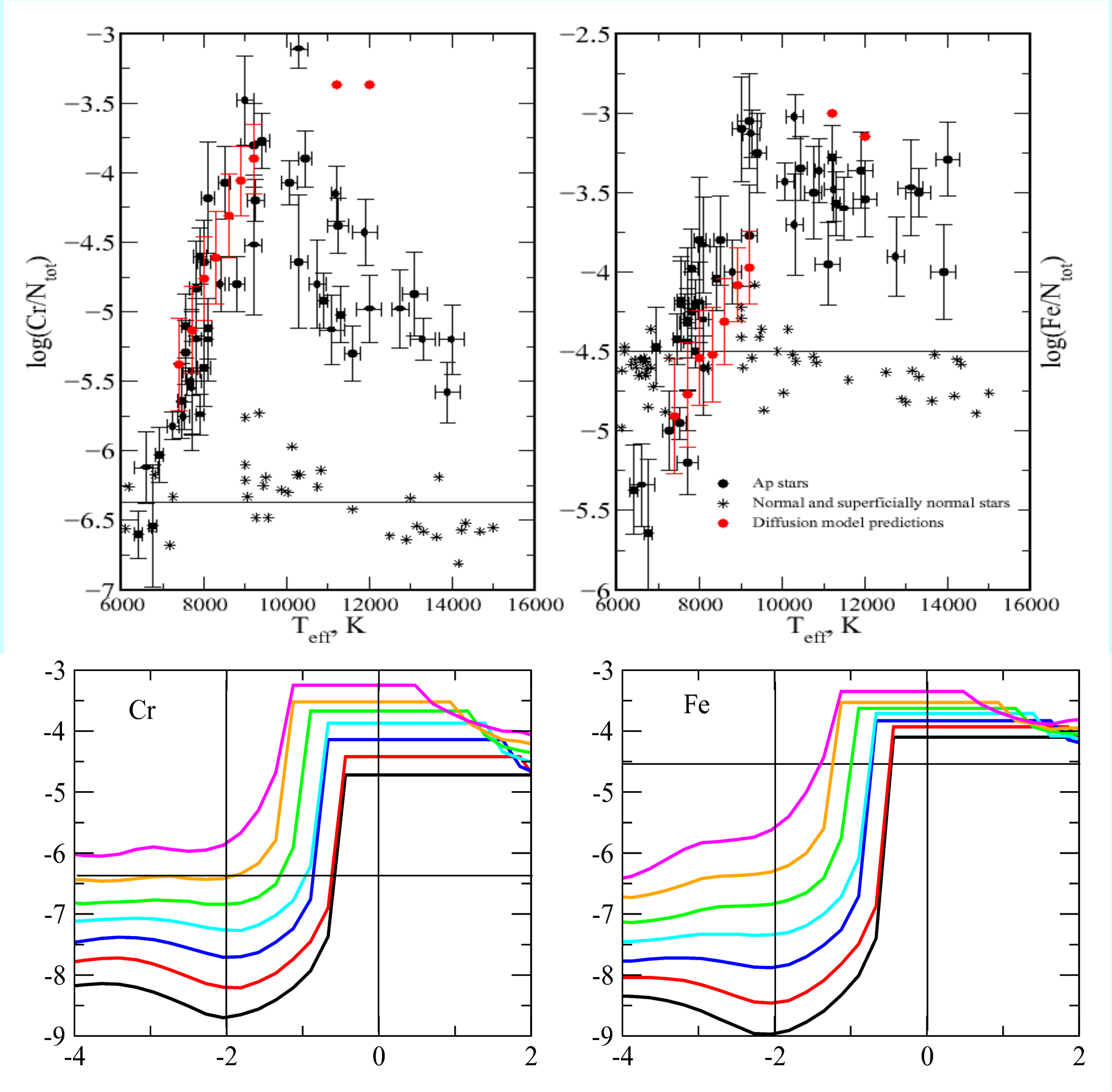
Temperature dependence of the mean Cr and Fe abundances in the atmospheres of Ap stars.

(Ryabchikova, 2005, Astr. Letters, 31, 388)

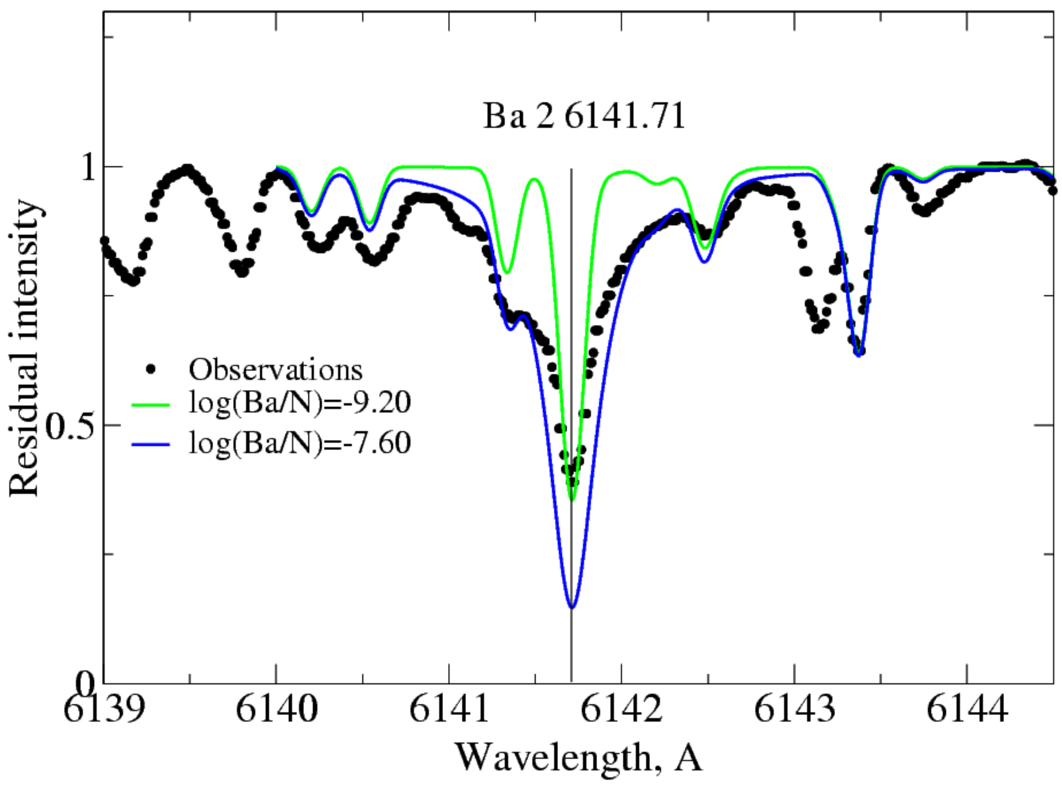


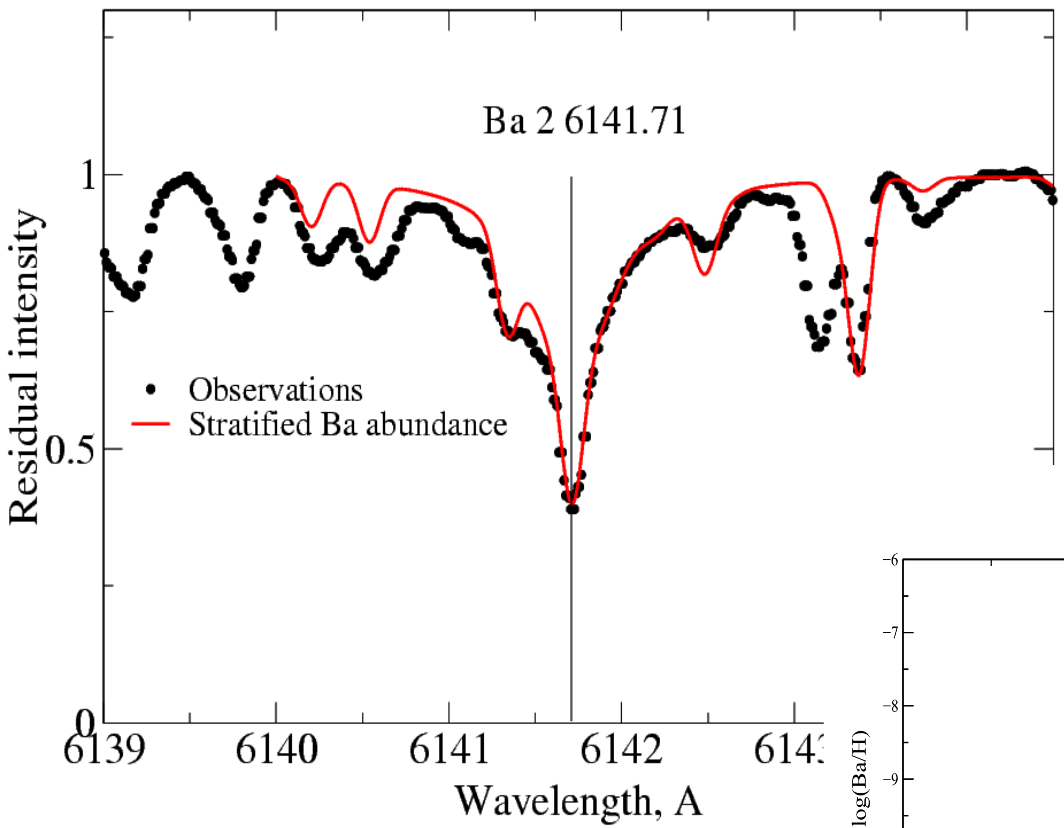
Theoretical distributions of the chosen elements derived in self-consistent diffusion model atmosphere calculations:

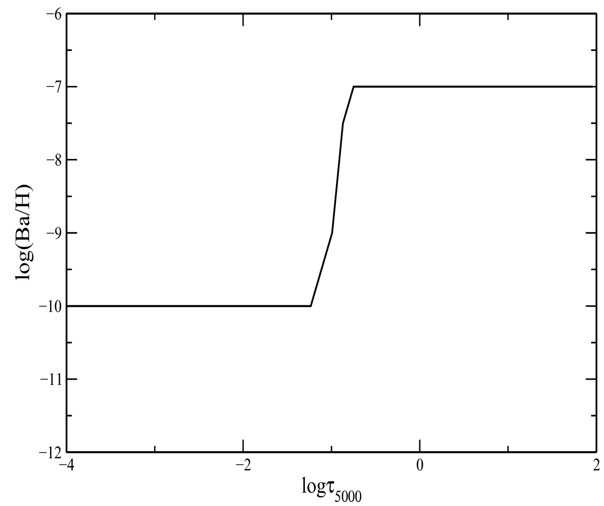
According to LeBlanc & Monin. 2004, IAU Symp.224, 193-200



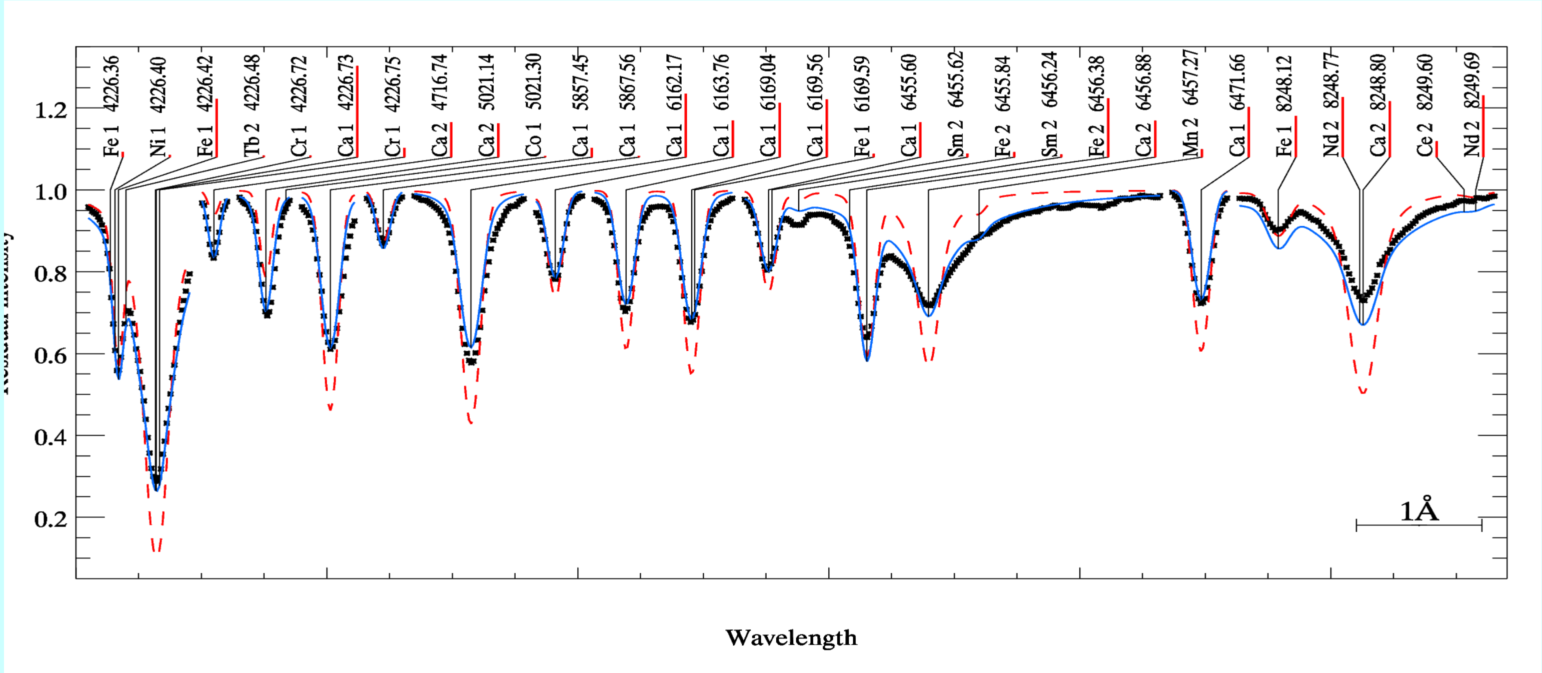
Impossibility to fit line core and line wings with the same abundance

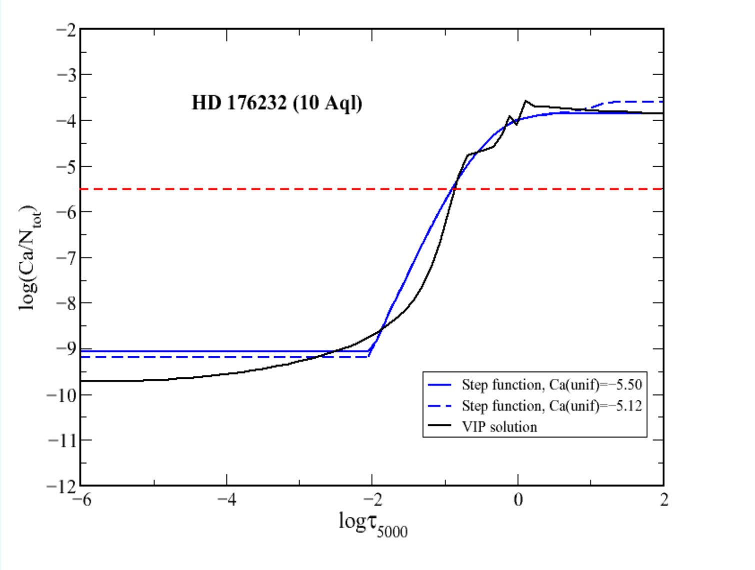



Ba 2 6141.71
Observations
Stratified Ba abundance
Residual intensity
0
0.5
1
6139
6140
6141
6142
Wavelength, A


log(Ba/H)
−6
−7
−8
−9
−10
−11
−12
−4
−2
0
2
logτ5000

Stratification analysis

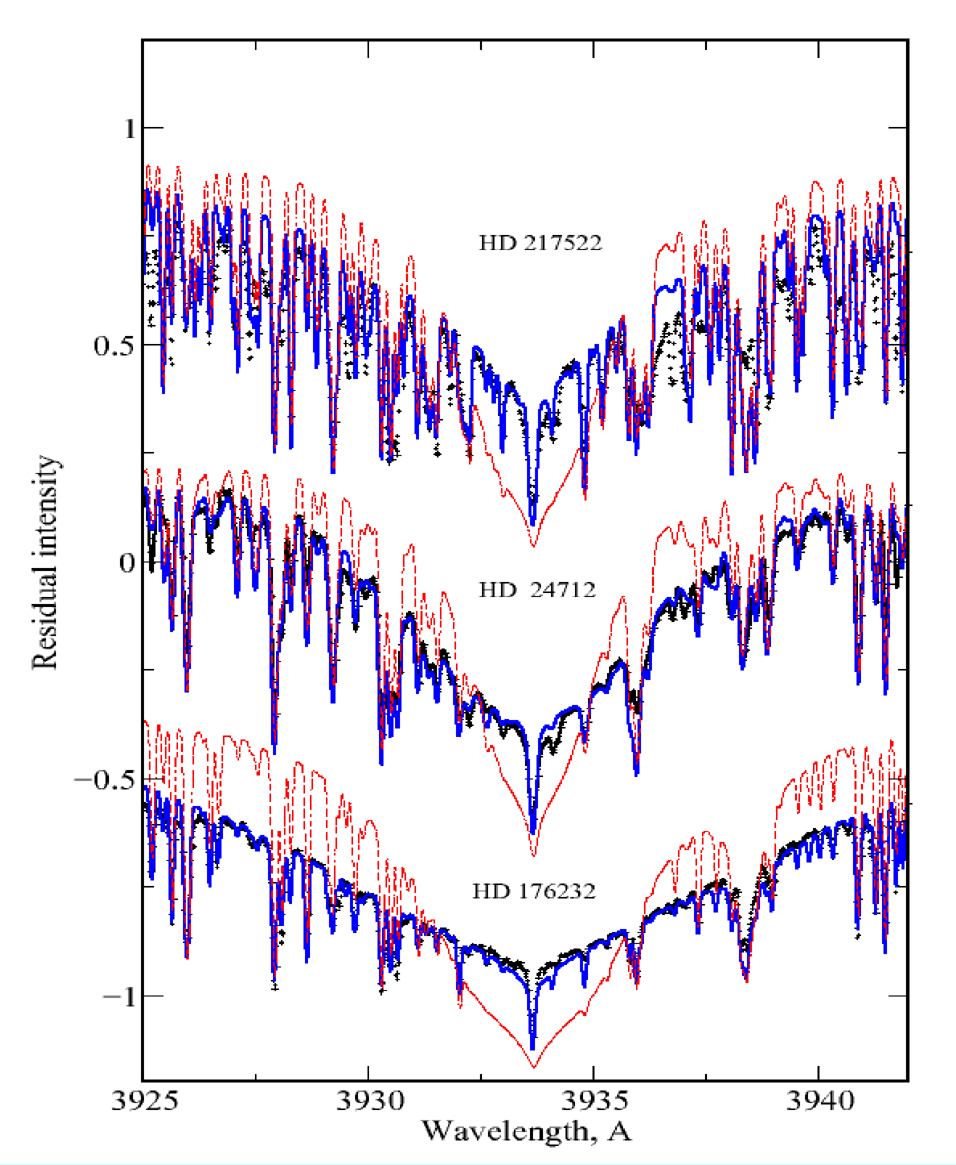




Startification analysis may be performed by step function approximation with ***ddafit*** code written by O.Kochukhov *(Ryabchikova et al. 2005, A&A, 438, 973)* or by

vertical inverse problem solution (VIP) - *Kochukhov et al. 2006, A&A, 460, 831*

Ca II 3933 line in Ap stars



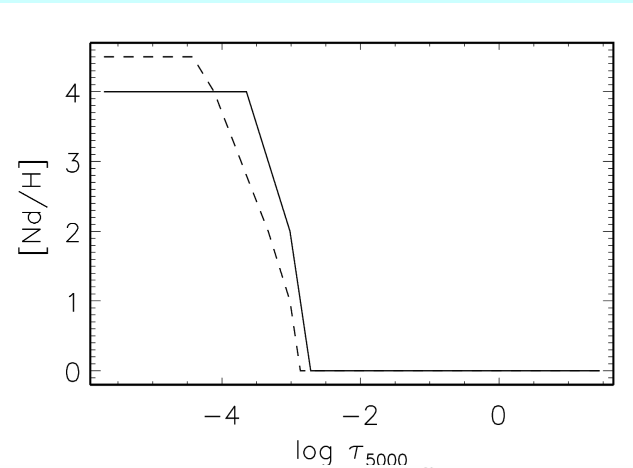
Stratified Ca distribution (blue line) explains the unusual shape (very narrow line core and shallow wings) of resonance Ca II lines in spectra of cool Ap stars compared to the uniform vertical Ca distribution (red dashed line)

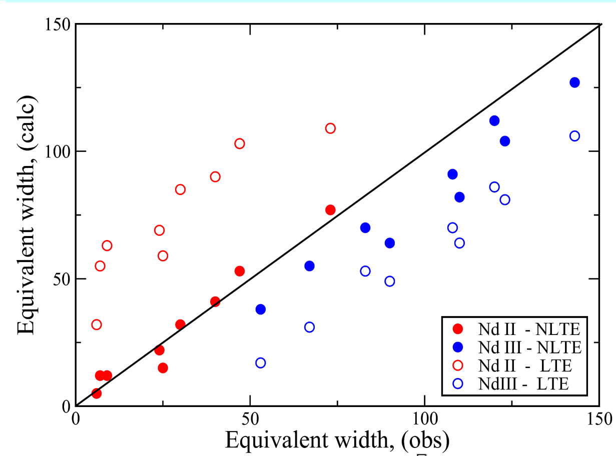
Element concentration in upper atmosphere

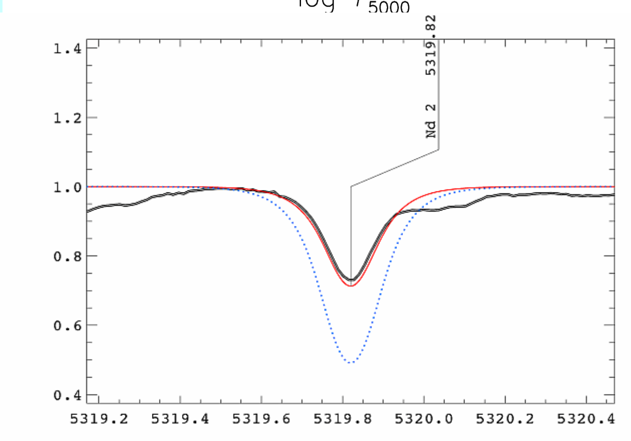
Nd distribution in the atmospheres of roAp stars. NLTE calculations by Mashonkina et al. (2005)

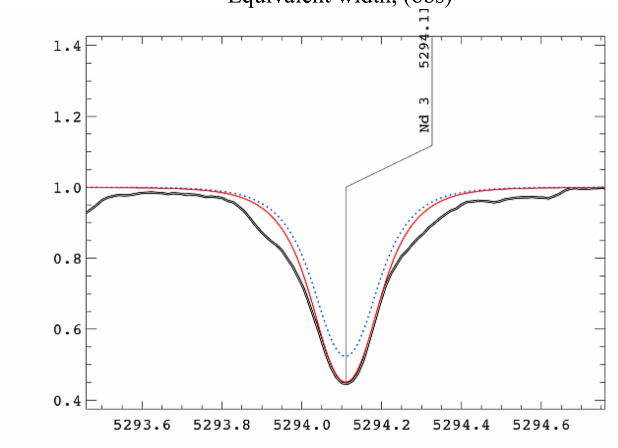
roAp star γ Equ

Introducing the enhanced Nd layer above logτ <-3 and taking into account NLTE effects we can fit both Nd II and Nd III lines (red line) while it's impposible with homogeneous Nd vertical distribution

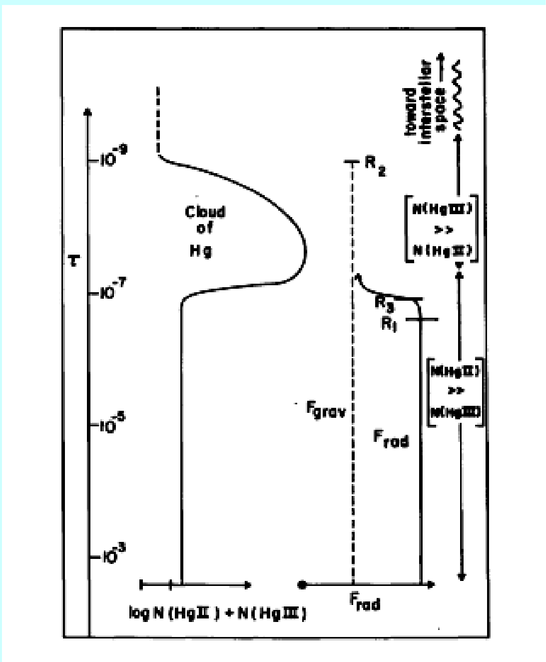








Michaud et al. (1974): high cloud of heavy elements



Blue horizontal branch stars

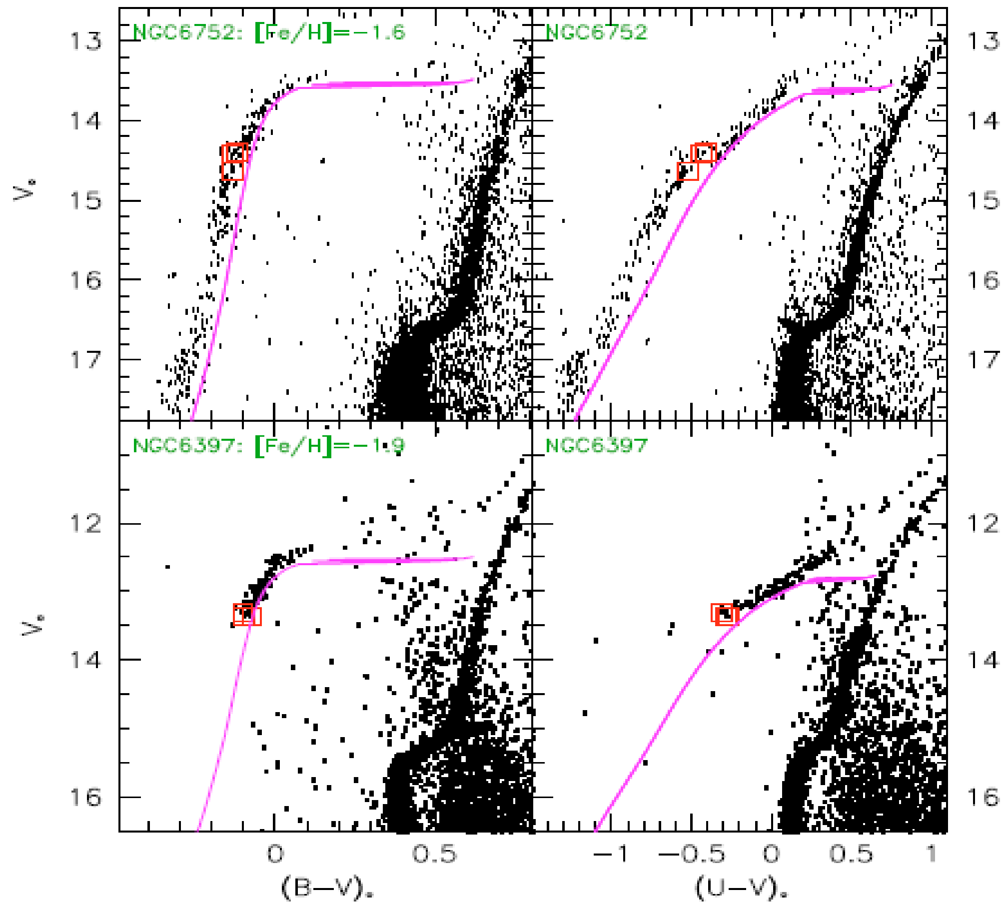
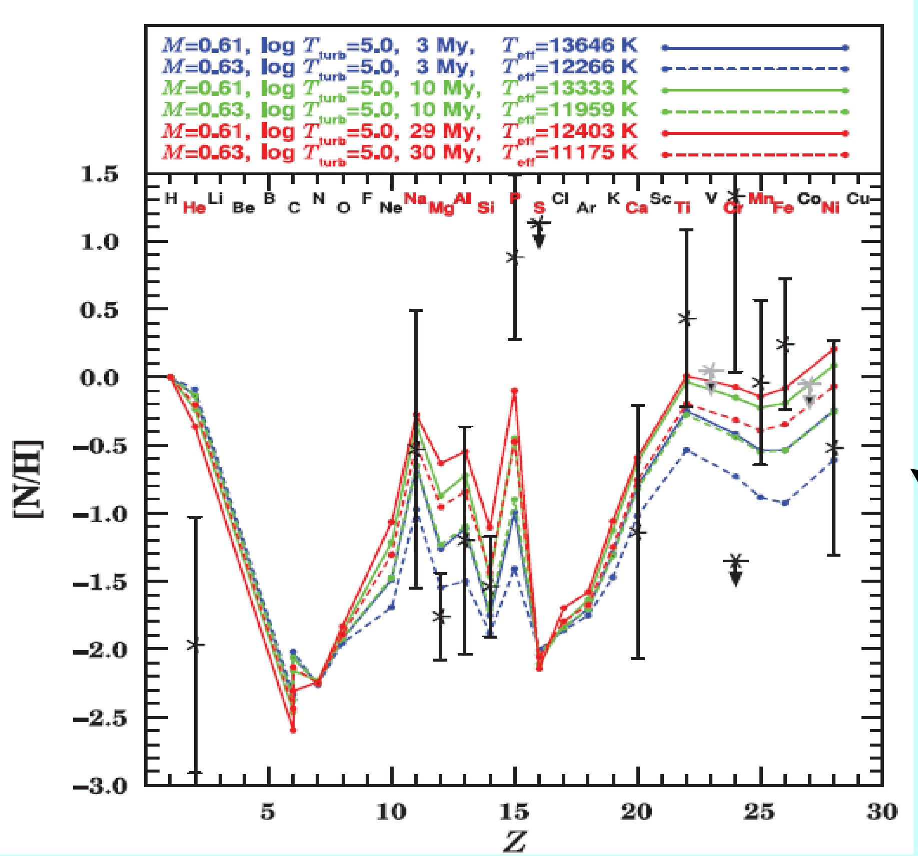


Fig. 1. *Left panels* display the classical V, $(B - V)$ colour–magnitude diagrams of NGC 6397 (*lower left*) and NGC 6752 (*upper left*). For both clusters, the studied BHB samples are plotted as open squares. Appropriate metallicity ZAHB models from Pietrinferni et al. (2006) are also plotted. Right panels display the respective ultraviolet V, $(U - V)$ diagrams. In the case of NGC 6752, the location of the Grundahl et al. (1999) u-jump is easily distinguished at $(U - V) \simeq -0.4$.

Stratification in the atmospheres of BHB stars



Behr (2003) found that BHB stars with Teff>11200 K in 6 metal-poor globular clusters rotate slowly and have strongly enhanced metal abundances compared to cluster metallicity.

Michaud et al. (2008, ApJ, 675, 1223) performed diffusion calculations and showed that the observed anomalies may be explained in the frames of diffusion theory

Theoretical self-consistent diffusion atmospheric models

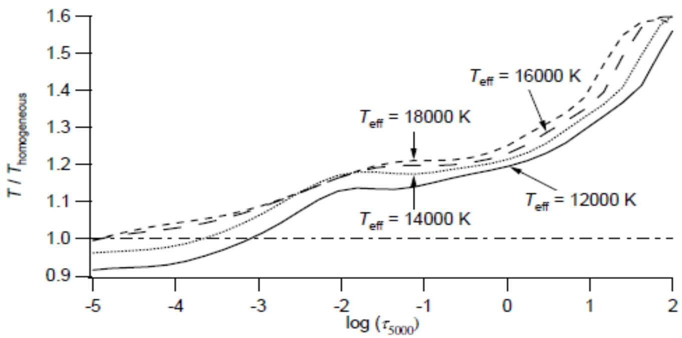


Figure 1. The ratio of the temperature as a function of optical depth in various models including stratification to that of a chemically homogeneous model with metallicity of -1.5 dex solar of the same effective temperature and surface gravity. The dotted-dashed line shows the position of a ratio of one.

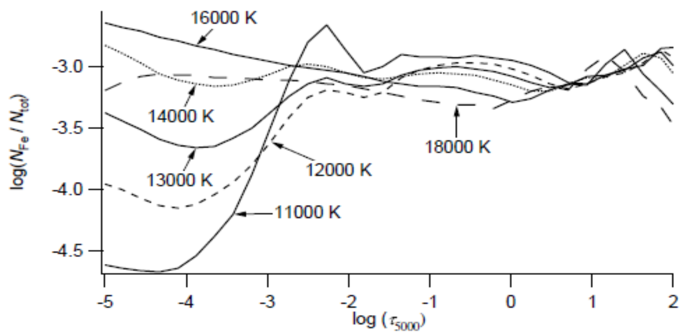
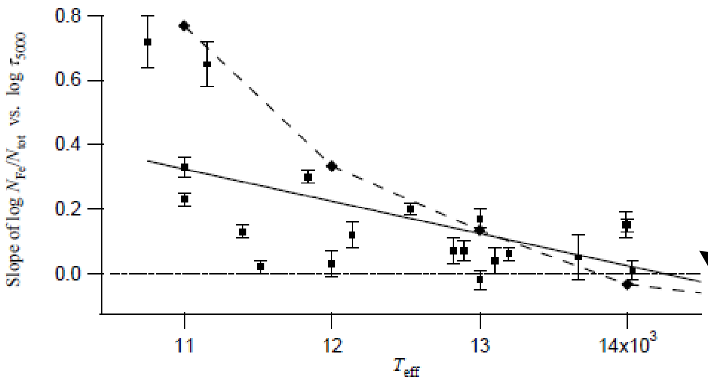


Figure 2. Abundance of Fe relative to optical depth for self-consistent model atmospheres of BHB stars with T_{eff} from 11000 K to 18000 K.

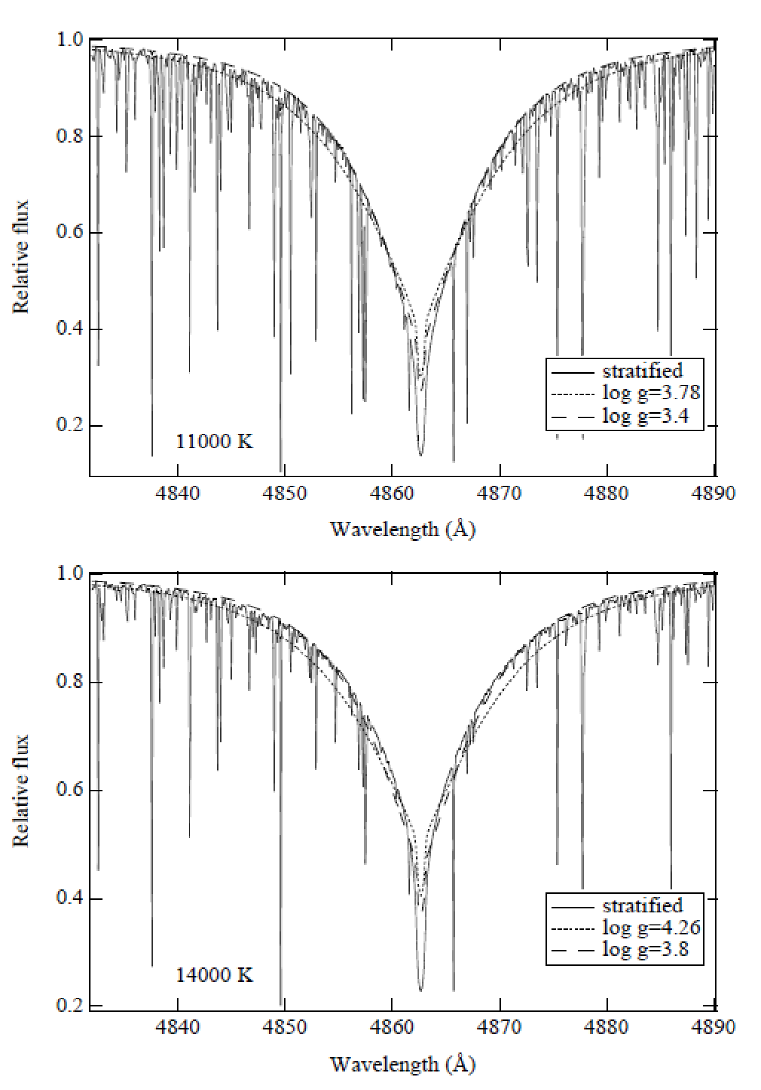


Blue horizontal-branch stars (BHB)
Teff = 11000 – 14000 K

Taken from F. Leblanc, A. Hui-Bon-Hoa, V. Khalack, 2010, MNRAS

dashed line shows the abundance slope predicted in stratified models

Blue horizontal-branch stars (BHB)
Teff = 11000 – 14000 K



Stratified models allow to solve the problem of the lower gravity than typical cluster value, derived for BHB stars with Teff>11200 K by hygrogen line prifile fitting with homogeneous abundance distribution models.

Taken from F. Leblanc, A. Hui-Bon-Hoa, V. Khalack, 2010, MNRAS

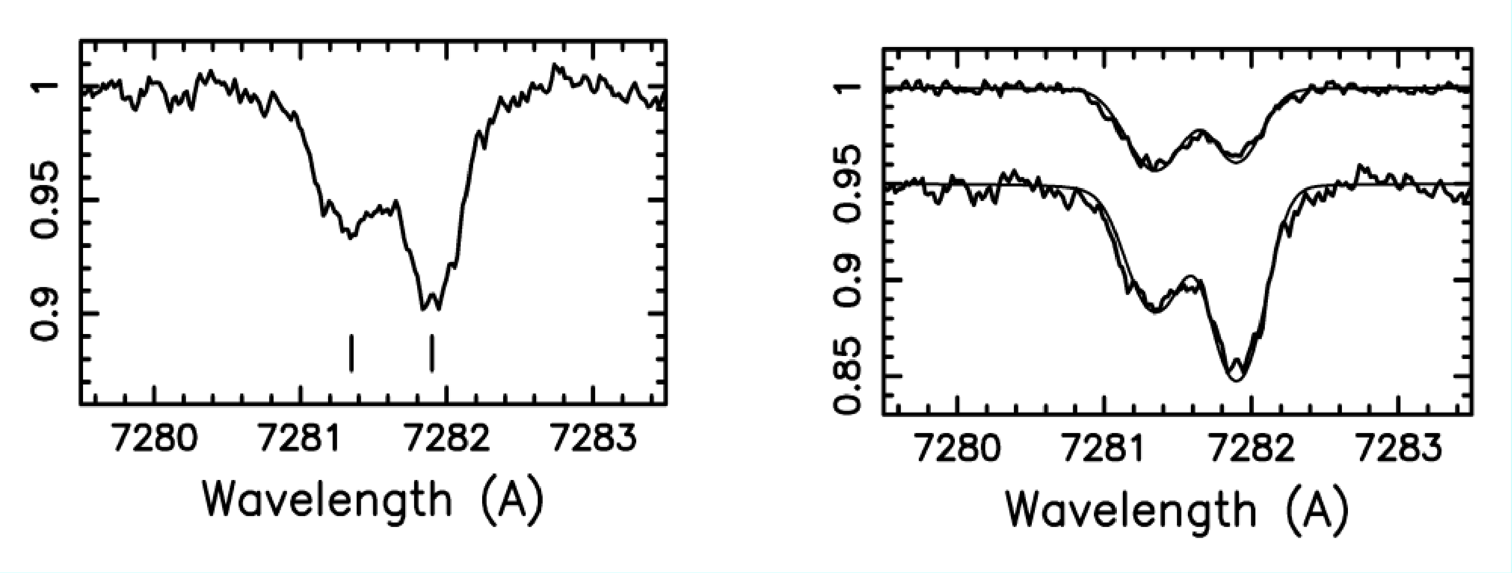
ISOTOPES

$^3He/^4He$ anomaly in hot stars

HR 7467 (15500g37) – top | **3 Cen A (17500g41) - bottom**

^{3}He: -0.90 ($-2.36 < \log\tau < -1.64$); -2.20 ($\log\tau > -1.64$) | -1.10 ($-2.65 < \log\tau < -1.16$); -2.50 ($\log\tau > -1.16$)

^{4}He: -2.00 ($\log\tau < -0.23$); -1.10 ($\log\tau > -0.23$) | -1.40 ($-0.52 < \log\tau < 0.7$); -2.00 ($\log\tau > 0.7$)



Taken from:

Bohlender, D. 2005, in *Element Stratification in Stars: 40 Years of Atomic Diffusion*, eds. G. Alecian, O. Richard and S. Vauclair, EAS Publ. Ser., 17, 83

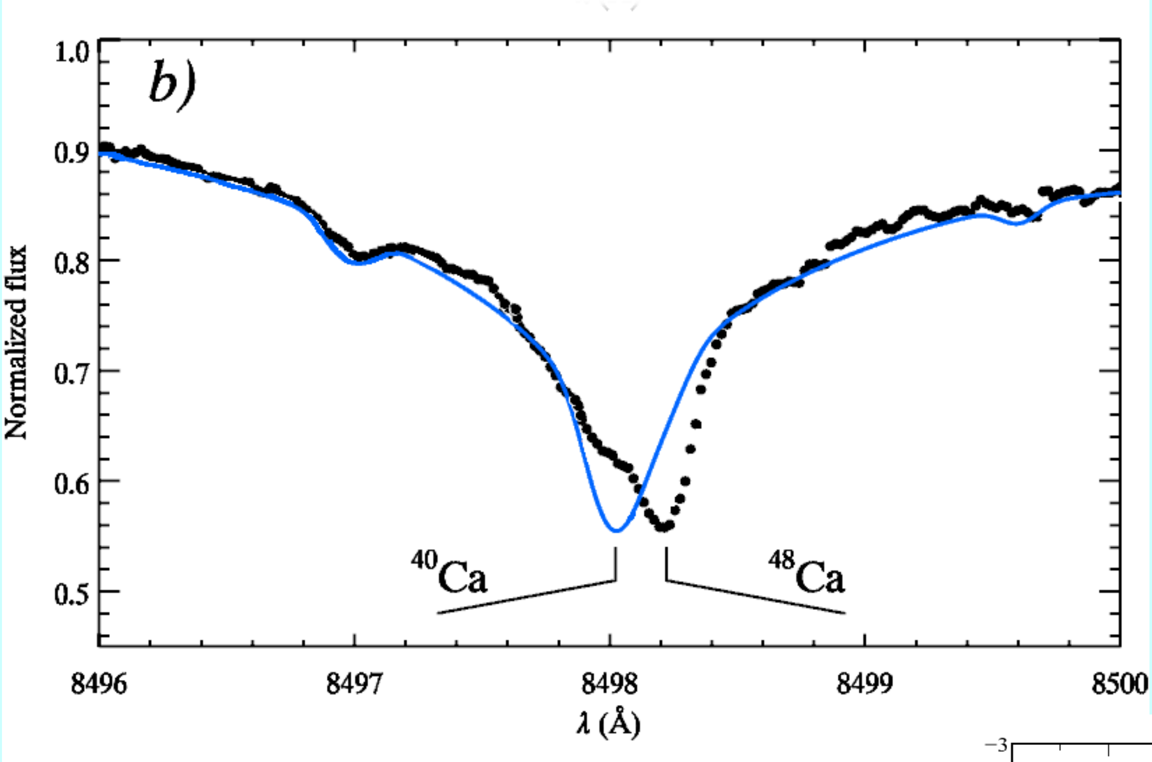
Ca isotope anomaly

First, Ca isotopes in IR triplet lines were found in HgMn stars by Castelli & Hubrig (2004)

In cool Ap stars wavelength shifts due to ^{48}Ca isotope were reported by Cowley & Hubrig (2005) and studied extensively by Cowley et al. (2007). These authors derived Ca startification for 2 Ap stars.

Full analysis of Ca stratification + isotopic modelling for 23 Ap stars was performed by Ryabchikova, Kochukhov & Bagnulo (2005, 2007).

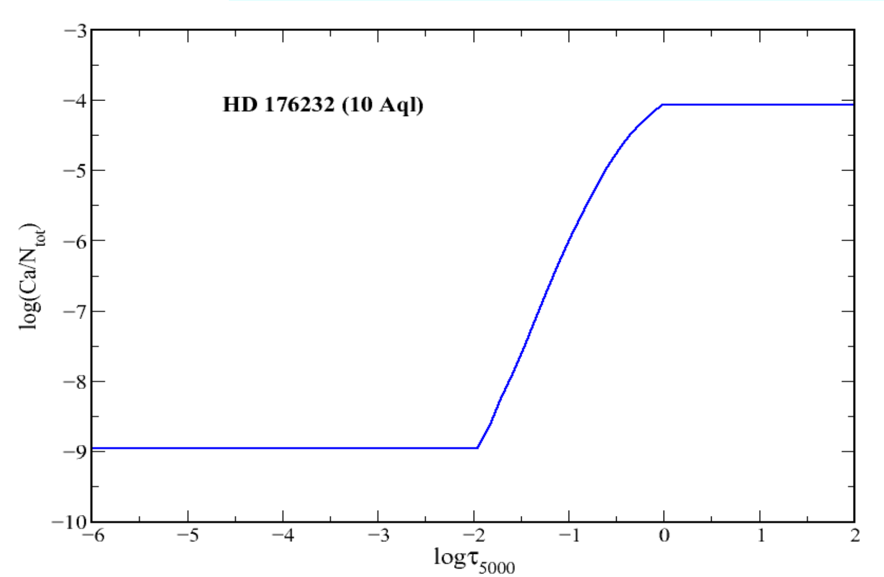
Ca isotopic shifts in BHB stars were found by Hubrig et al. 2009, A&A 499, 865

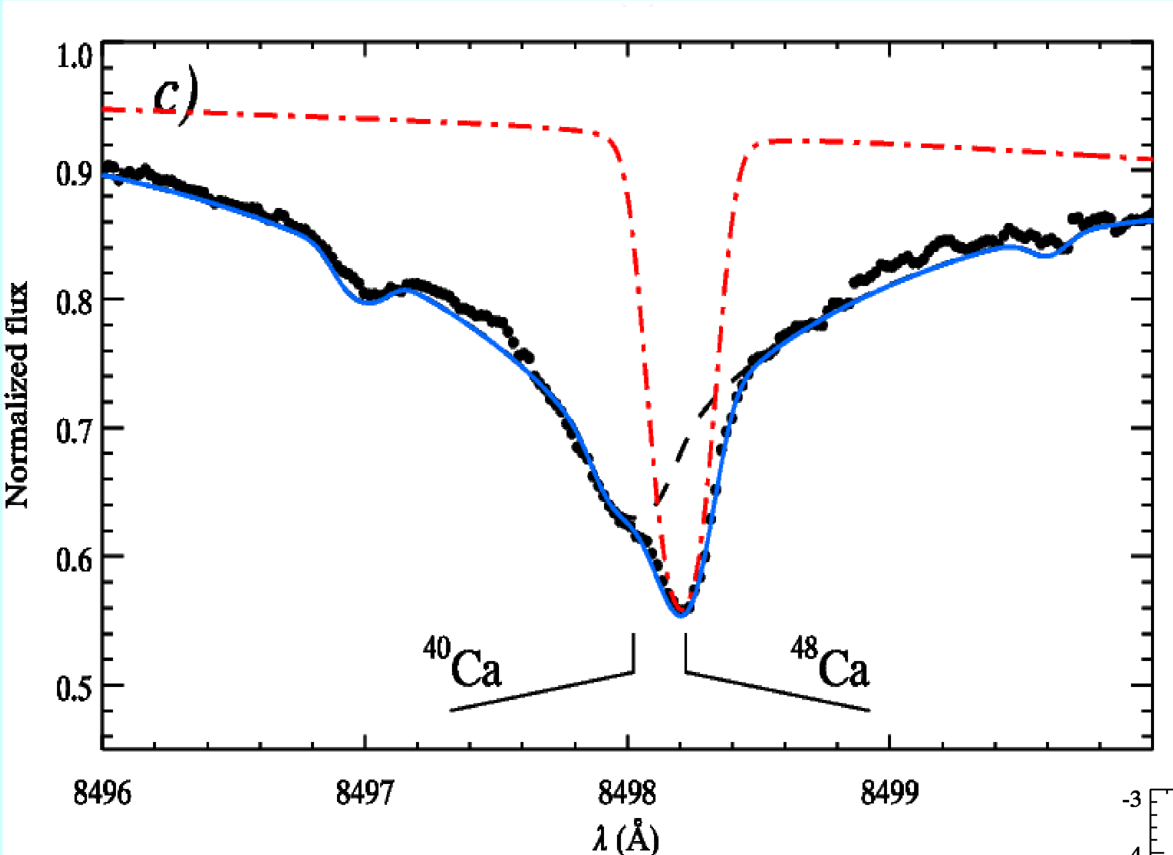


Ca II 8498 line in 10 Aql.

Blue line represents synthetic line profile calculated with the Ca stratification shown below by black line

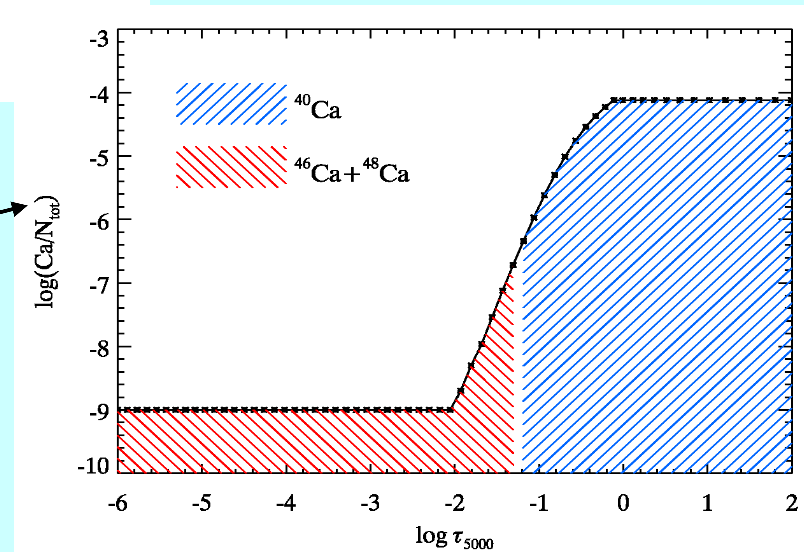
Ca stratification derived from the Ca optical lines





Ca II 8498 line in 10 Aql.

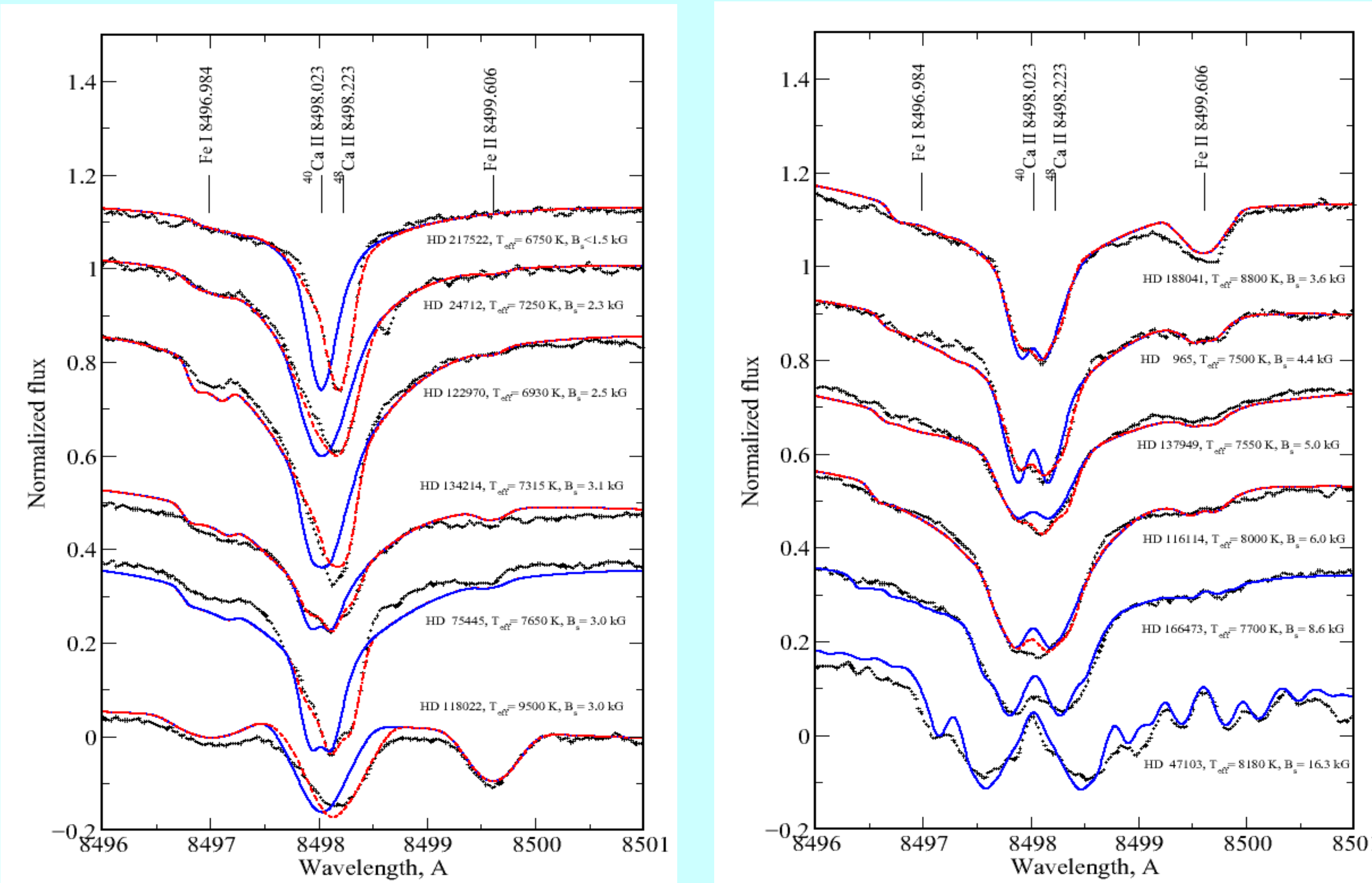
The fit to the observed Ca II line in 2-component stratified atmosphere



Proposed separation of the Ca isotopes

Ca II 8498 line in spectra of Ap stars with T_{eff} < 9500 K

blue line indicates theoretical line profiles in Ca-stratified but isotopically homogeneous atmospheres, while red line shows the same profile in the atmospheres with isotopic separation



Ca II IR triplet lines in BHB stars

(from Hubrig et al. 2009)

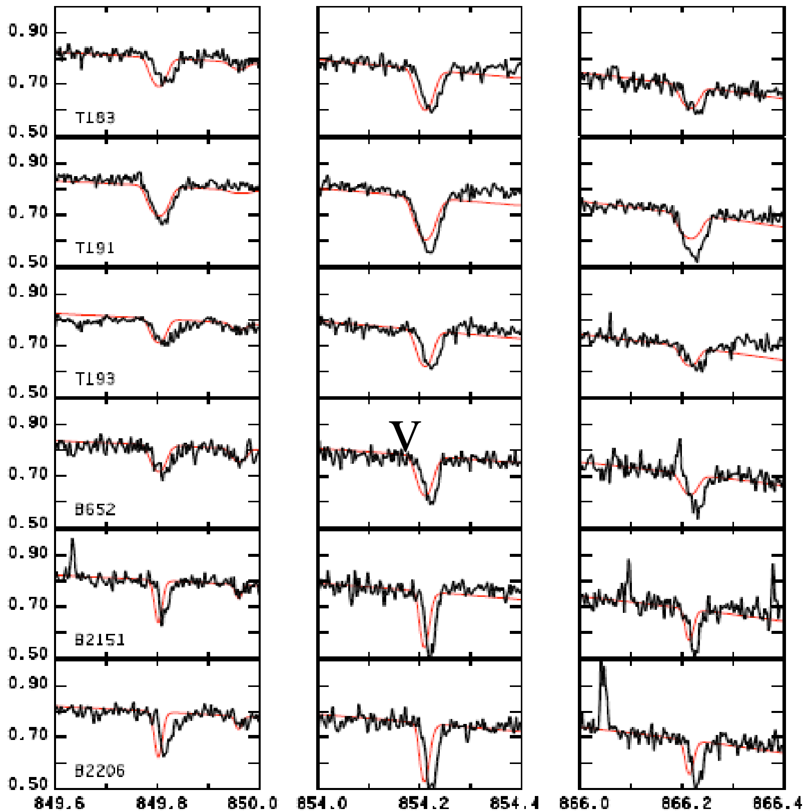
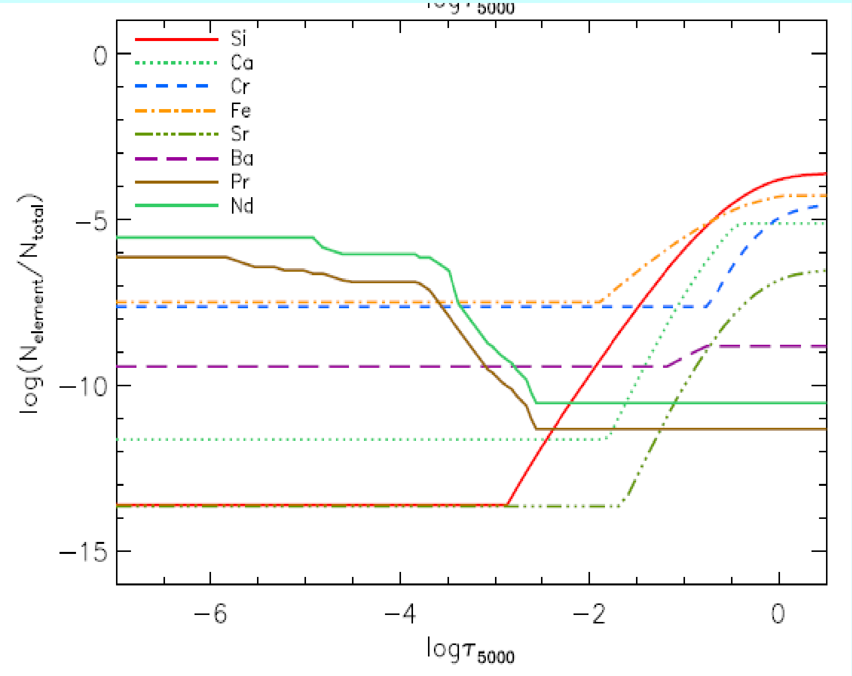


Fig. 6. Observed Ca II triplet shifts in all studied stars. The computed profiles assuming the terrestrial isotopic mixture are presented by thin lines.

The line profiles calculated with the terrestrial isotopic Ca composition are shown by the red line.

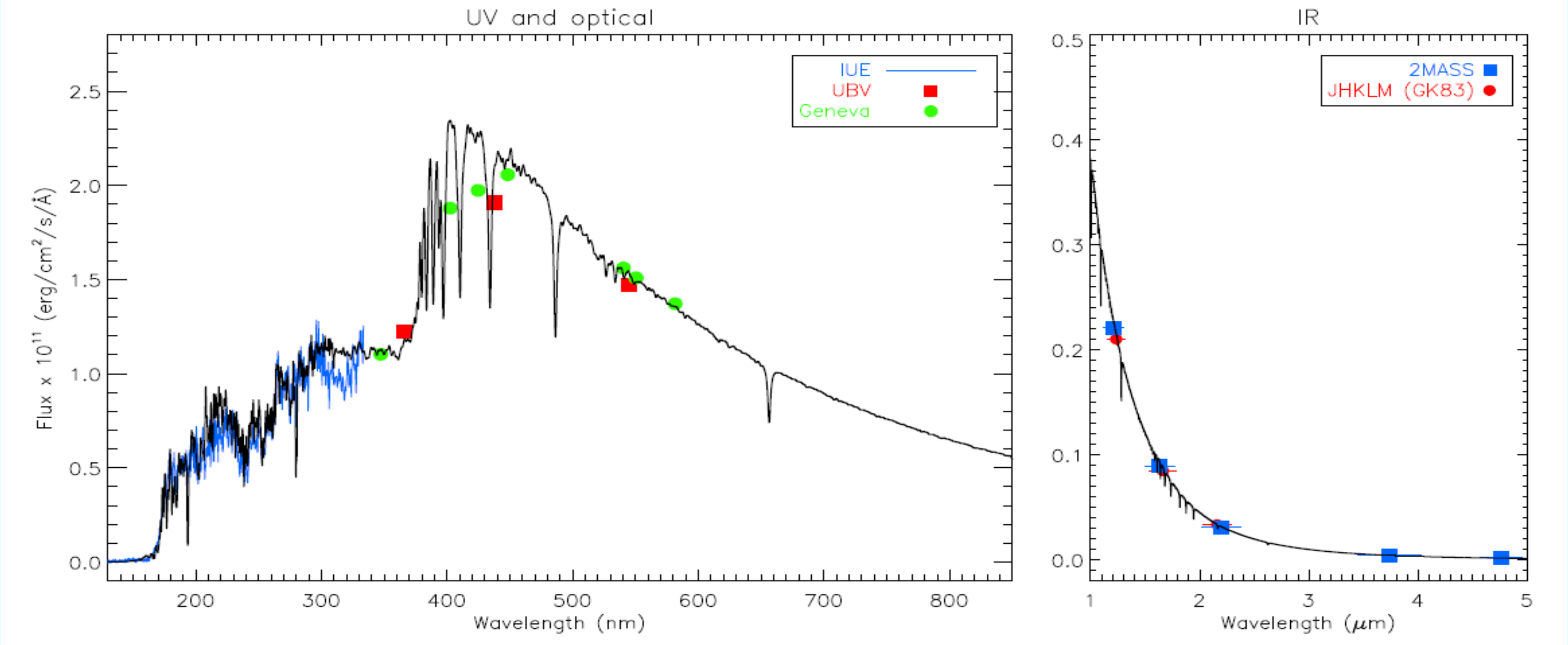
Spectral energy distribution with the stratified abundances



HD 24712

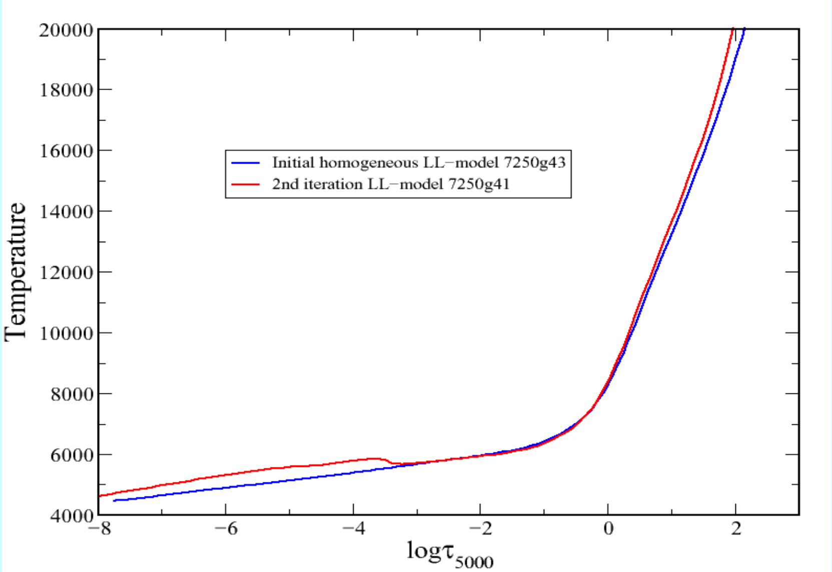
Shulyak, Ryabchikova, Mashonkina, & Kochukhov. 2009, A&A, 499, 879

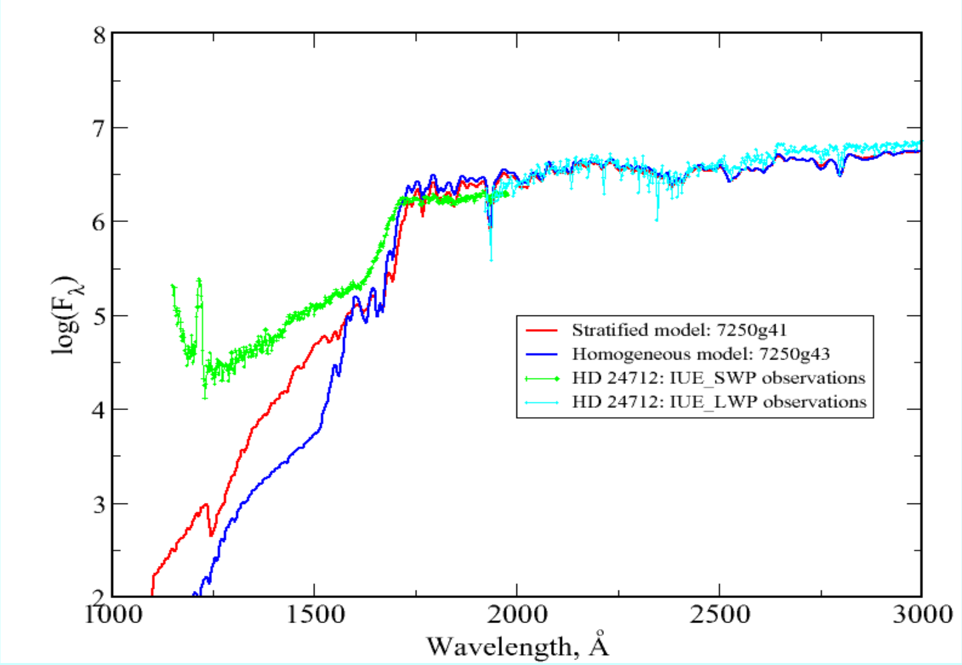
T_{eff}=7250 K, log g=4.1,
R=1.77±0.04 $R_☉$



HD 24712

The influence of chemical stratification on the atmospheric structure and on the emergent flux





The use of the temperature distribution obtained with stratification effects improves significantly parameters of pulsation model (magnetic field) for HD 24712 :

Saio et al. 2010, MNRAS, 401, 1299

γ Equ

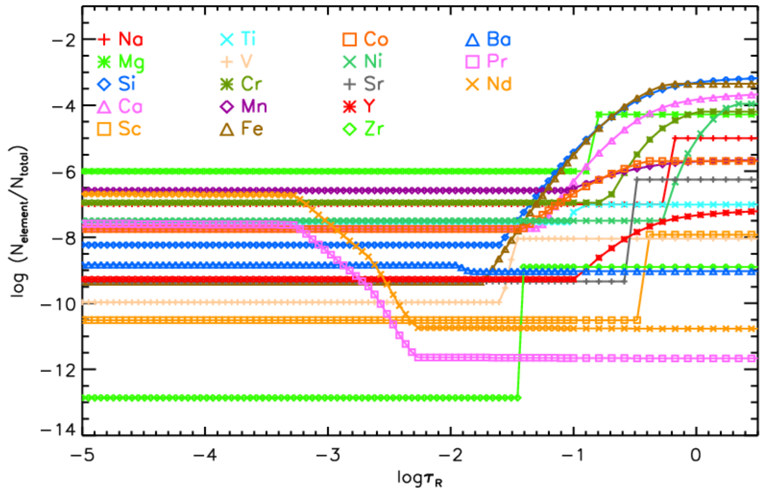
18 chemical elements are analysed for stratification:

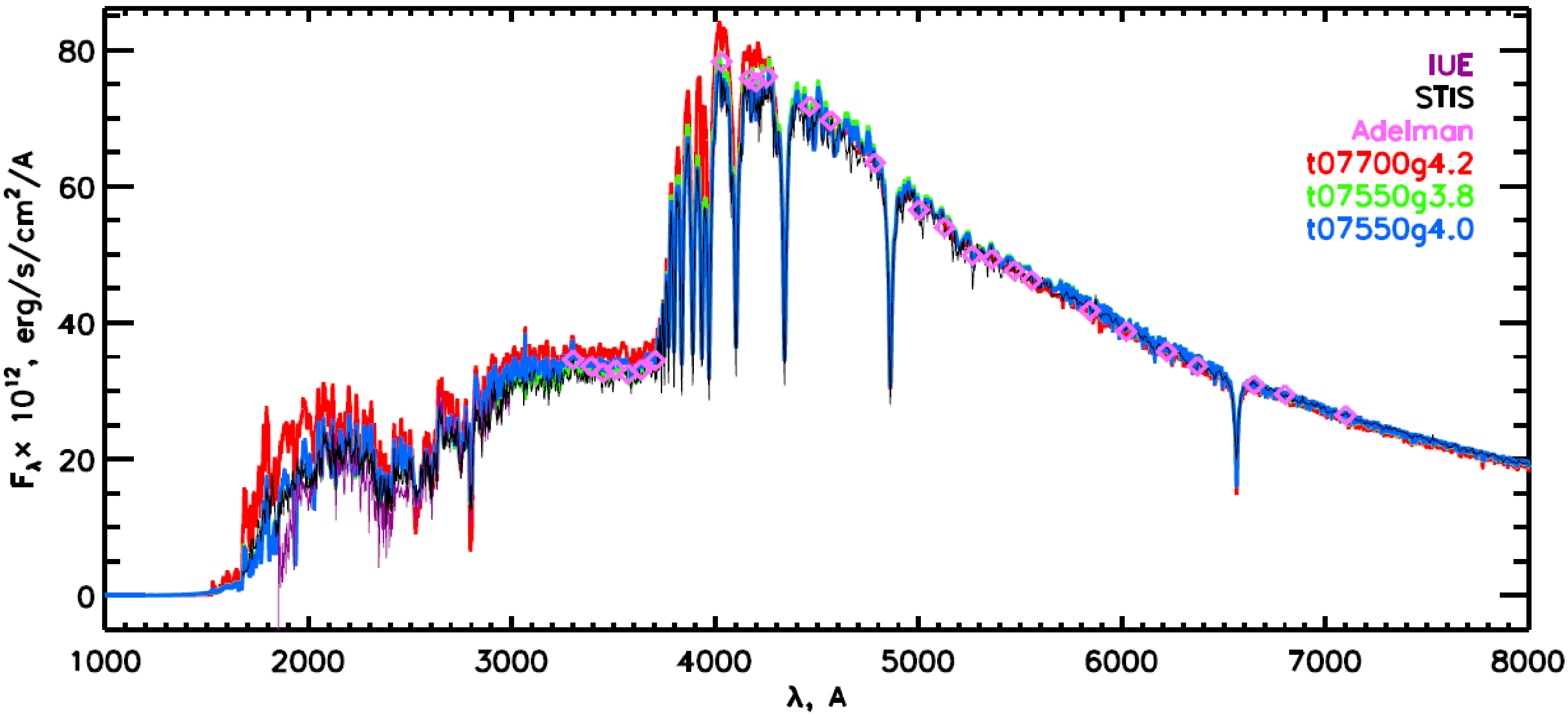
Starting model:

T_{eff}=7700 K, log g=4.2, R=2.03±0.08 $R_☼$

Final model:

T_{eff}=7550 K, log g=4.0, R=2.07±0.05 $R_☼$

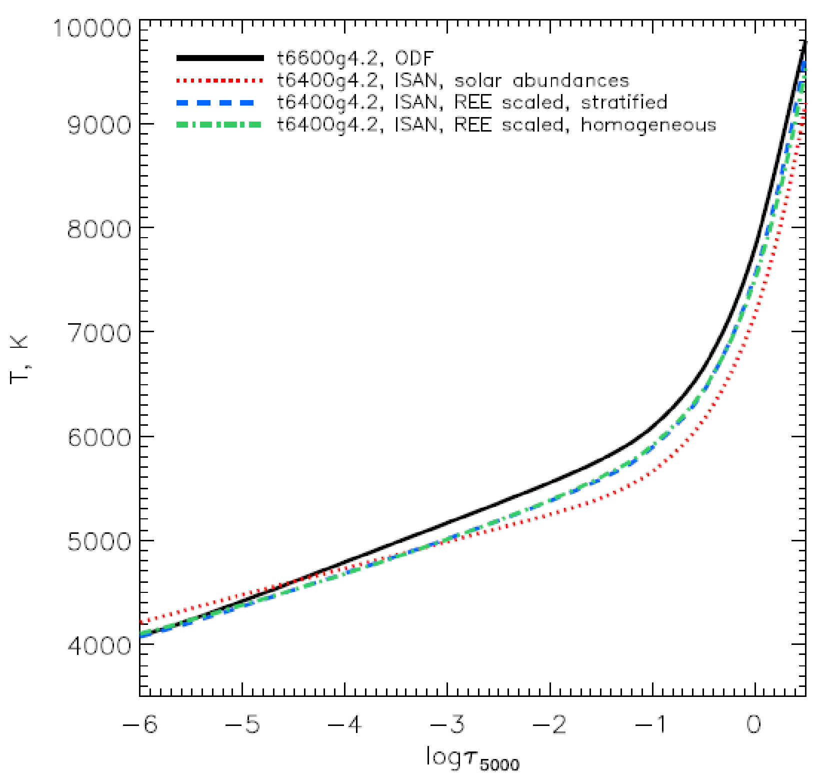


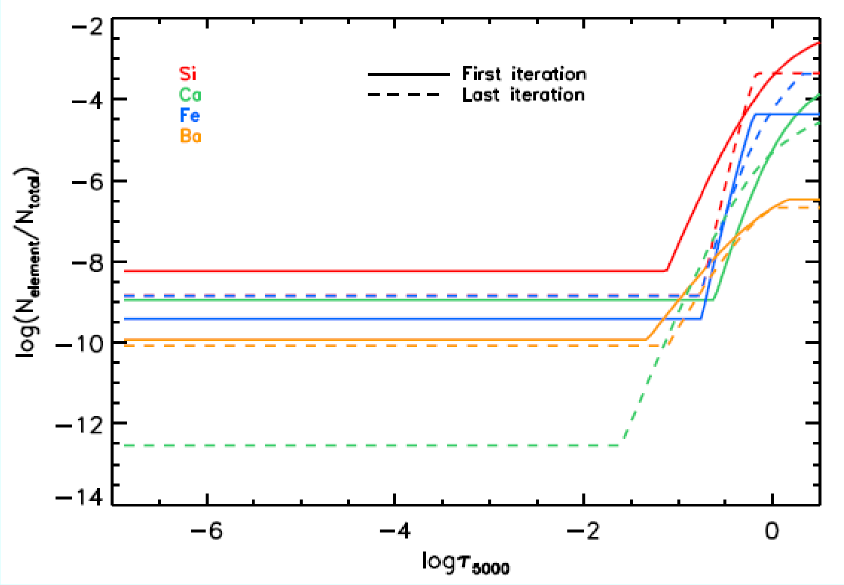


HD 101065 – Przybylski' star

Shulyak, Ryabchikova, Kildiyarova, & Kochukhov. (2010)

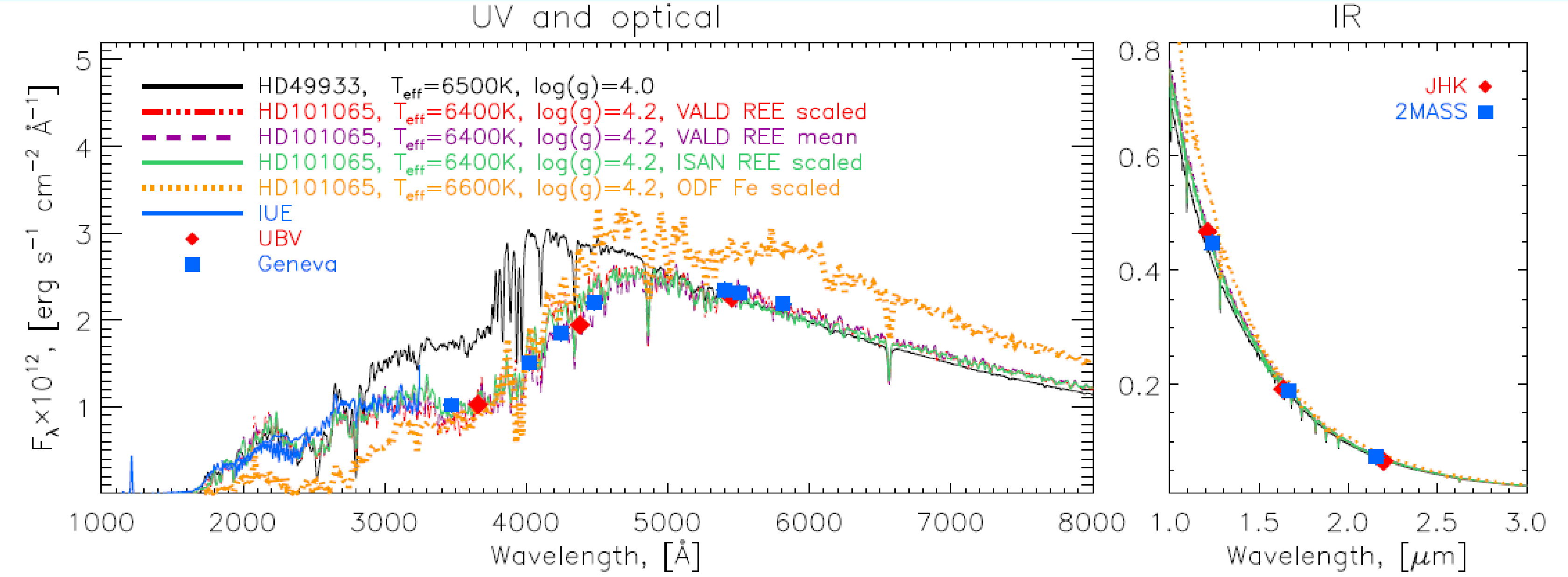
T_{eff}=6400 K, log g=4.2
R=1.98±0.03 $R_{\odot}$
B_s=2.3 kG

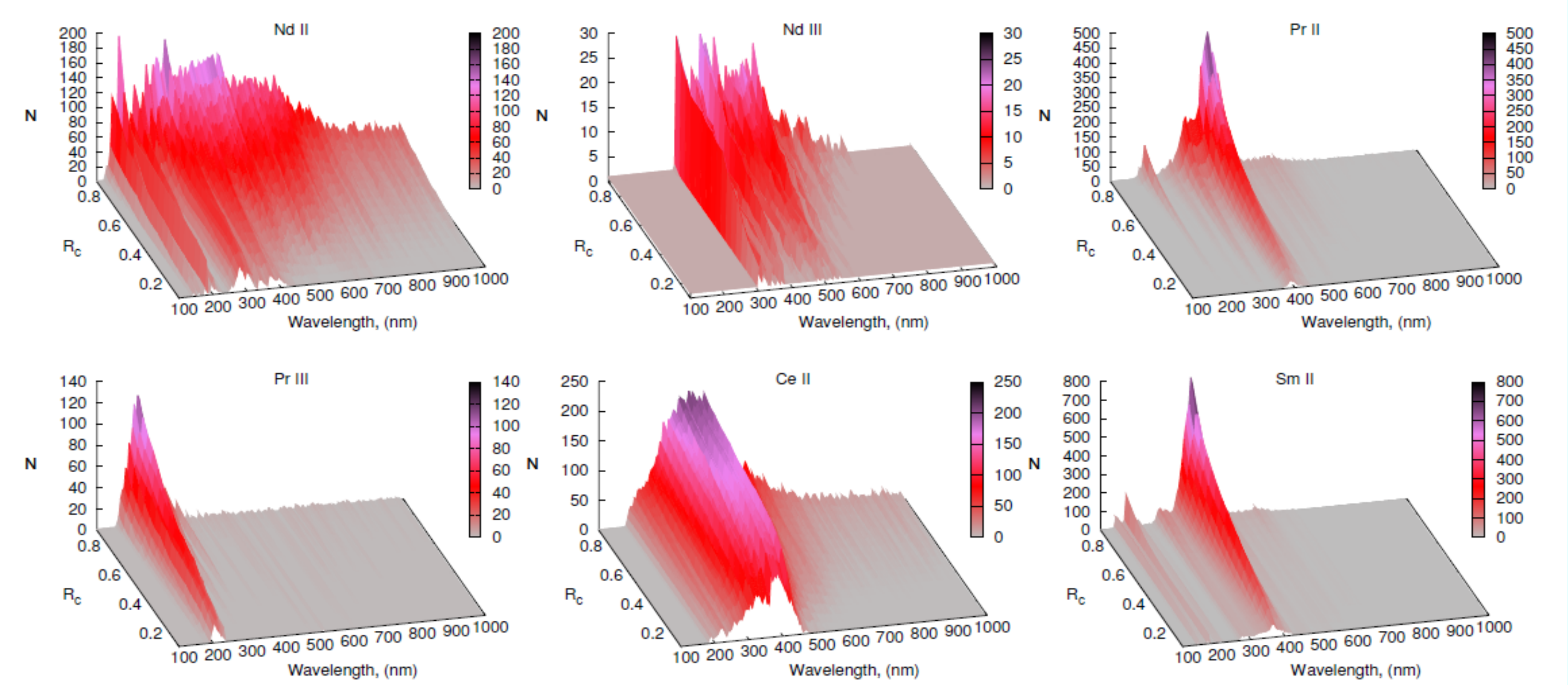




T_{eff}=6622±100 K, log g=4.06±0.04,
R=1.90±0.08 $R_{\odot}$, B_p=8.7 kG
from seismic models
Mkrtichian et al. 2008, A&A, 490, 1109

HD 101065 – Przybylski' star (flux distribution and influence of REE opacities)



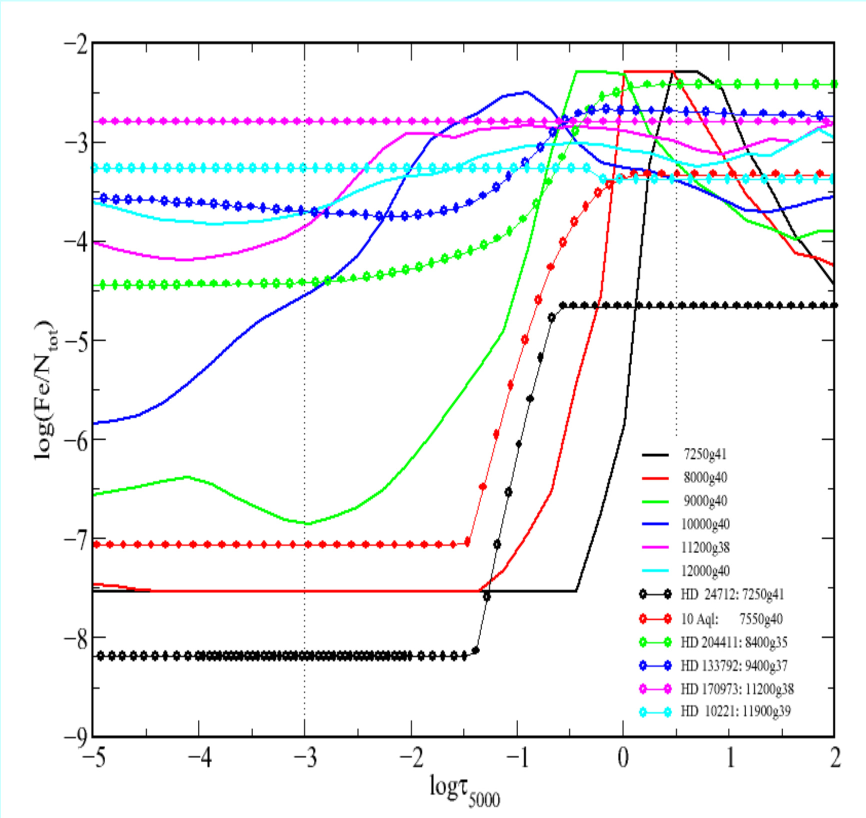


Theoretical self-consistent diffusion models.

Ap stars

Comparison between observed element distribution and theoretical predictions

F. LeBlanc: self-consistent calculations



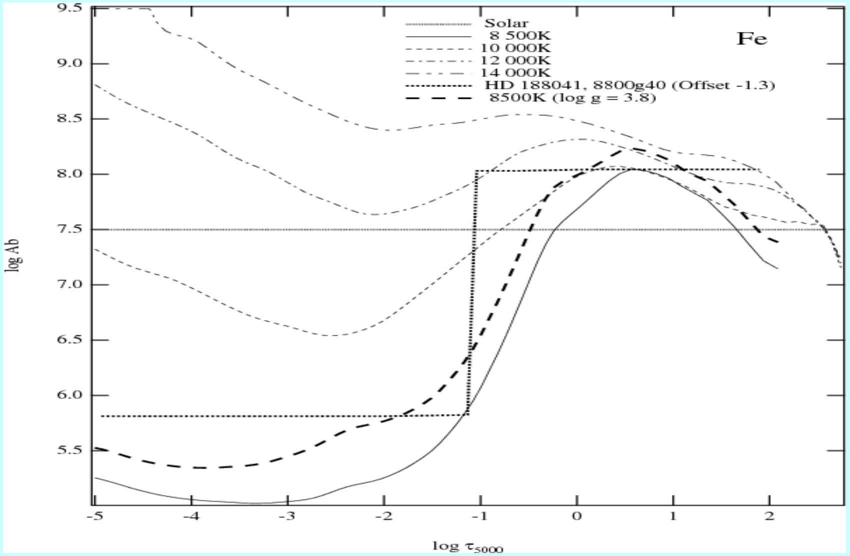


Fig. 8 from Alecian & Stift. 2010, A&A, 516, 53
Models without stratification

CONCLUSIONS

1. **Element stratification is observed in the stabilized stellar atmospheres (magnetic Ap stars, slowly rotating HgMn and BHB stars)**

2. **Element stratification manifests itself through the change of the observed line profiles and/or through the violation of ionization/excitation equilibrium**

3. **The chemical stratification derived from the observed line profiles follow the diffusion theory predictions**

4. **Elements may be concentrated in the deeper as well as in the upper atmospheric layers**

5. **Abundance stratification study with the concentration in the upper atmosphere requires NLTE**

6. **Differential stratification of the isotopes is observed in stellar atmospheres**

7. **Abundance stratification changes the structure of stellar atmosphere that results in change of emergent flux.**