Laurent Piau

Two tools to model the solar atmosphere

PICARD workshop

Observable Sun

A thin layer : photosphere ≈ 200 km ≈ 0.03 % $R_\odot$
chromosphere ≈ 2000 km

Characterized by :

* Cold 5 10^3 / 10^4 K & diffuse $\rho \approx 10^{-7} / 10^{-12}$ g. cm^{-3} conditions

* Energy transport : from convective to radiative
from opaque to transparent
\+ magnetic heating

* Dynamical behavior : active on short and medium time scales
Magnetism, convection, waves

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Modelling to understand the surface and
… to interpret the interior

Solar atmosphere models

Surface issues

1) Convection spatial and time scales

Turbulence : large Reynolds number ≈ 10^{12}

Compressible flow : $v_t/c_s \approx 0.2$

Rapid changes : τ ≈ a few minutes

2) Other physical reasons

convection/radiation interaction

Radiative transfer, opacities and NLTE effects …

Cold region $T < 10^4$ K : ionization H, He^+, He^{++}… chemistry

Magnetic field

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Empirical models

Theoretical models

Theoretical modelling of the stellar surface

One dimension tools

↗ Accurate resolution of the radiative transfer equation
↘ Approximate treatement of convection

ex : Atlas12

Two/three dimensions tools

↗ Direct computation of convection, realistic magnetic fields
↘ Radiative transfer by the group method

ex: Stagger

ATLAS12 code : 1D

1) Average stratification

2) ➔ Phenomenological prescription of convection

$$F_{conv} = K_{rad} T H_p^{-1} (\nabla - \nabla_{ad}) \Phi(S)$$

$$S = Ra * Pr = \frac{g \alpha_v \beta \Lambda^4}{\nu \chi} * \frac{\nu}{\chi}$$

a) Mixing length theory *(Böhm-Vitense 1958)* : one eddy Λ
b) Full spectrum of turbulence *(Canuto & Mazzitelli 1991 ...)* :
Kolmogorov cascade of eddies from Λ

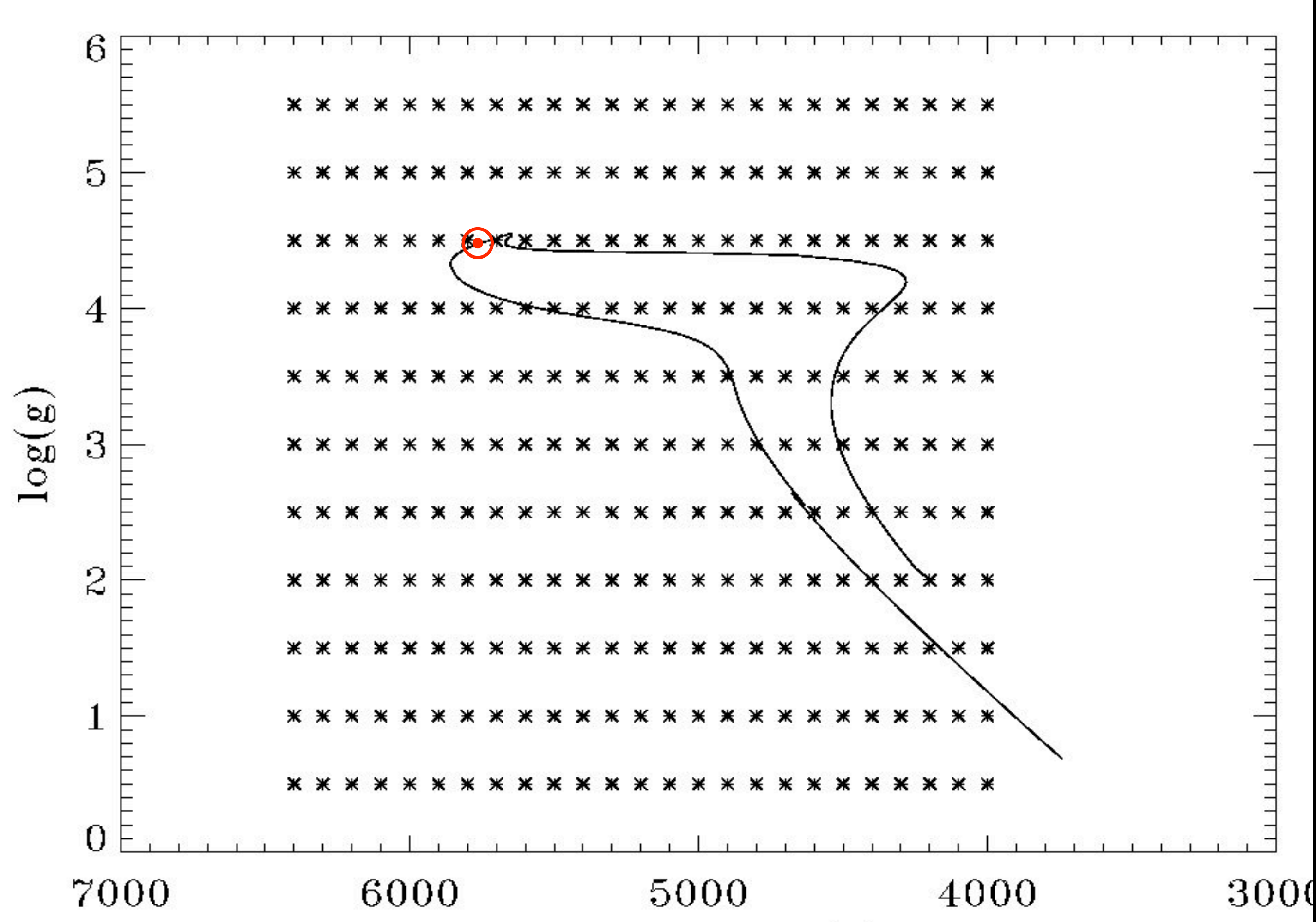
3) Log τ from -6 to 4 ➔ Radiative transfer equation

$$I_\nu - S_\nu = \frac{dI_\nu}{(\kappa_\nu + \sigma_\nu) \rho dz}$$

30 000 frequencies
58 millions of lines

Current grid of boundary conditions

Evolution track $1M_\odot$ from preMS to the tip of the RGB



Piau et al. (2010), in prep

STAGGER code : 3D

Parallel code: magnetohydrodynamics of the outer layers

Stein & Nordlund (1998)

Method

Hydrodynamics (compressible) and induction equations

∂x : finite differences order 2-6

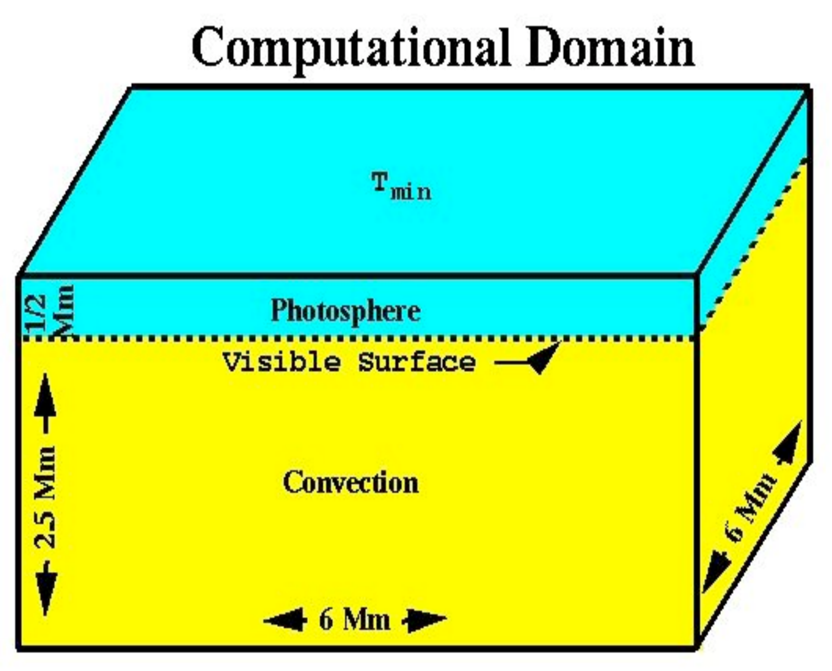
∂t : Runge-Kutta 2-3 order

Simulated domain

'Box in the star ' :

6Mm × 6Mm × 3 Mm

504 × 504 × 250 ⇒ 12 to 2 km meshes



Applications

Radiation hydrodynamics : lines formation

Magnetoconvection : thermal profile, surface magnetism…

Seismology : P_{turb} & entropy fluctuations

Frequencies, modes amplitudes…

STAGGER code : approximations

1) Convection : Large Eddy Simulation with Smagorinski subgrid

2) Radiation : group method

The transfer equation

$$I_\nu - S_\nu = cos\theta \frac{dI_\nu}{(\kappa_\nu + \sigma_\nu)\rho dz}$$

becomes

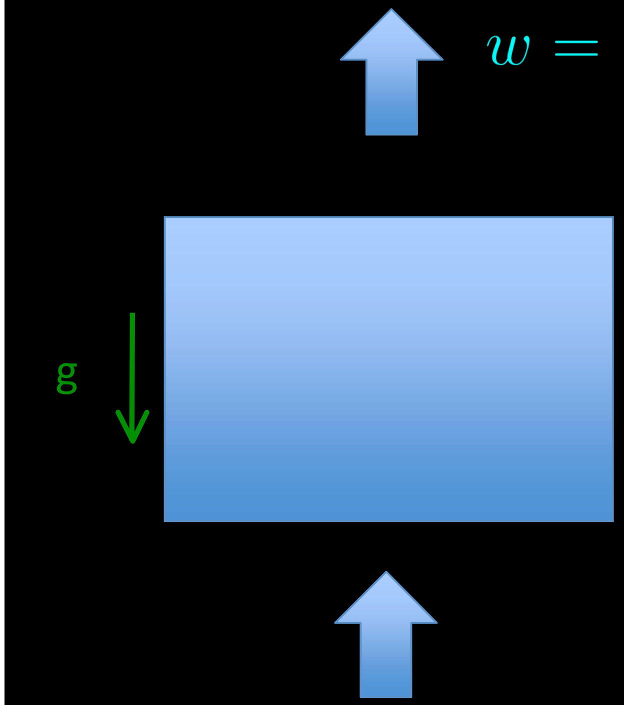
$$cos\theta \frac{\partial I_i}{\kappa_i \rho dz} = I_i - S_i$$

… and the radiative heating

$$Q_{rad} = 4\pi\rho \sum_{i=1,4} \kappa_i (J_i - S_i)\Delta\nu_i$$

Monochromatic opacity tables are necessary

Stagger : inputs / outputs



T_{eff}, P_{mag} $P_{turb} = \rho w^2$

$$w = \sqrt{\overline{v_v^2} - \bar{v_v}^2}$$

e, ρ, B

→ outputs : surface manifestations

↓

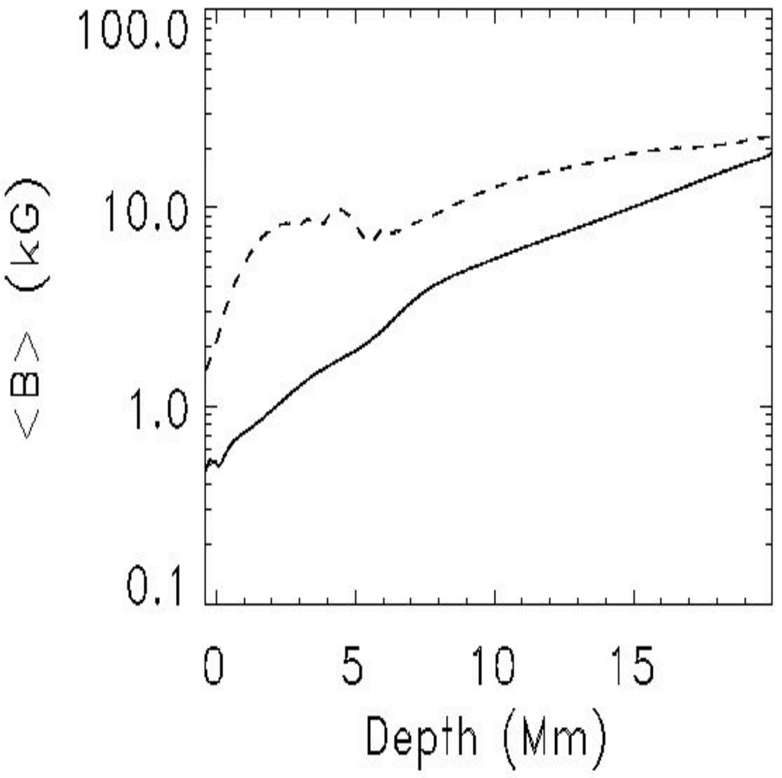
Stagger connects deep conditions
to surface behavior

↓

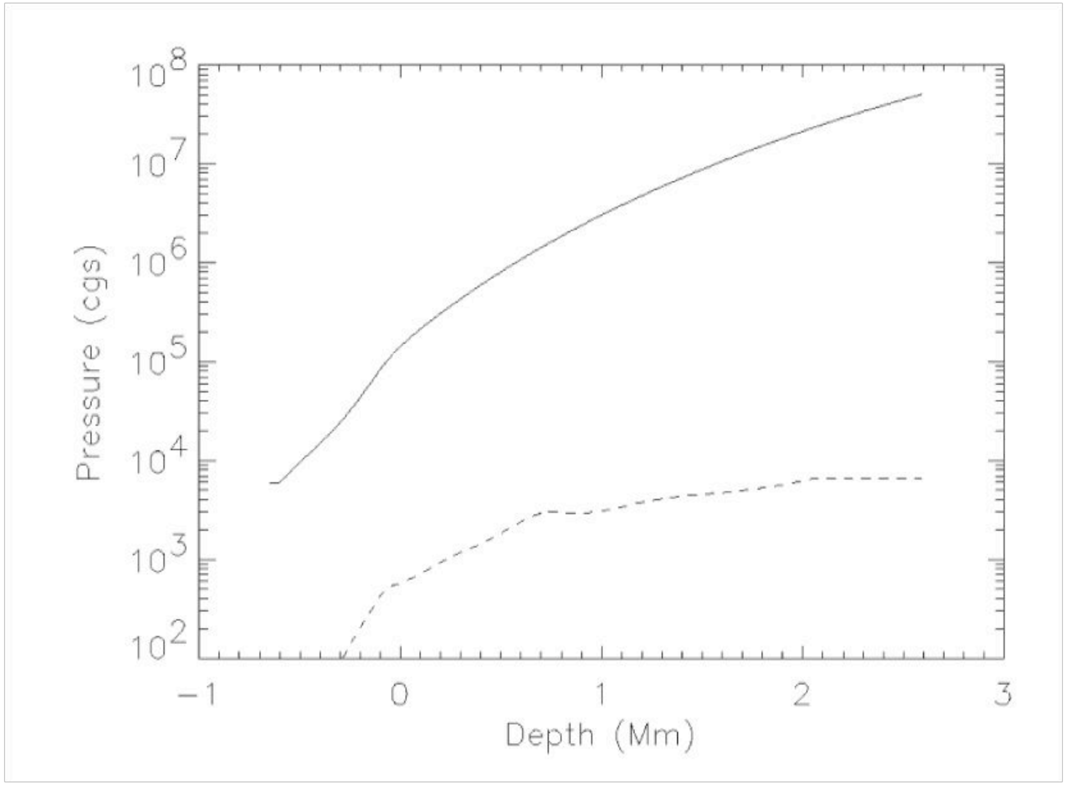
← inputs : deep conditions and large scales poloidal / toroidal B

From :
1D evolution codes with multiD prescriptions
2D evolution codes ex : *Li, Sofia et al. (2009)*

Stagger : some MHD computations



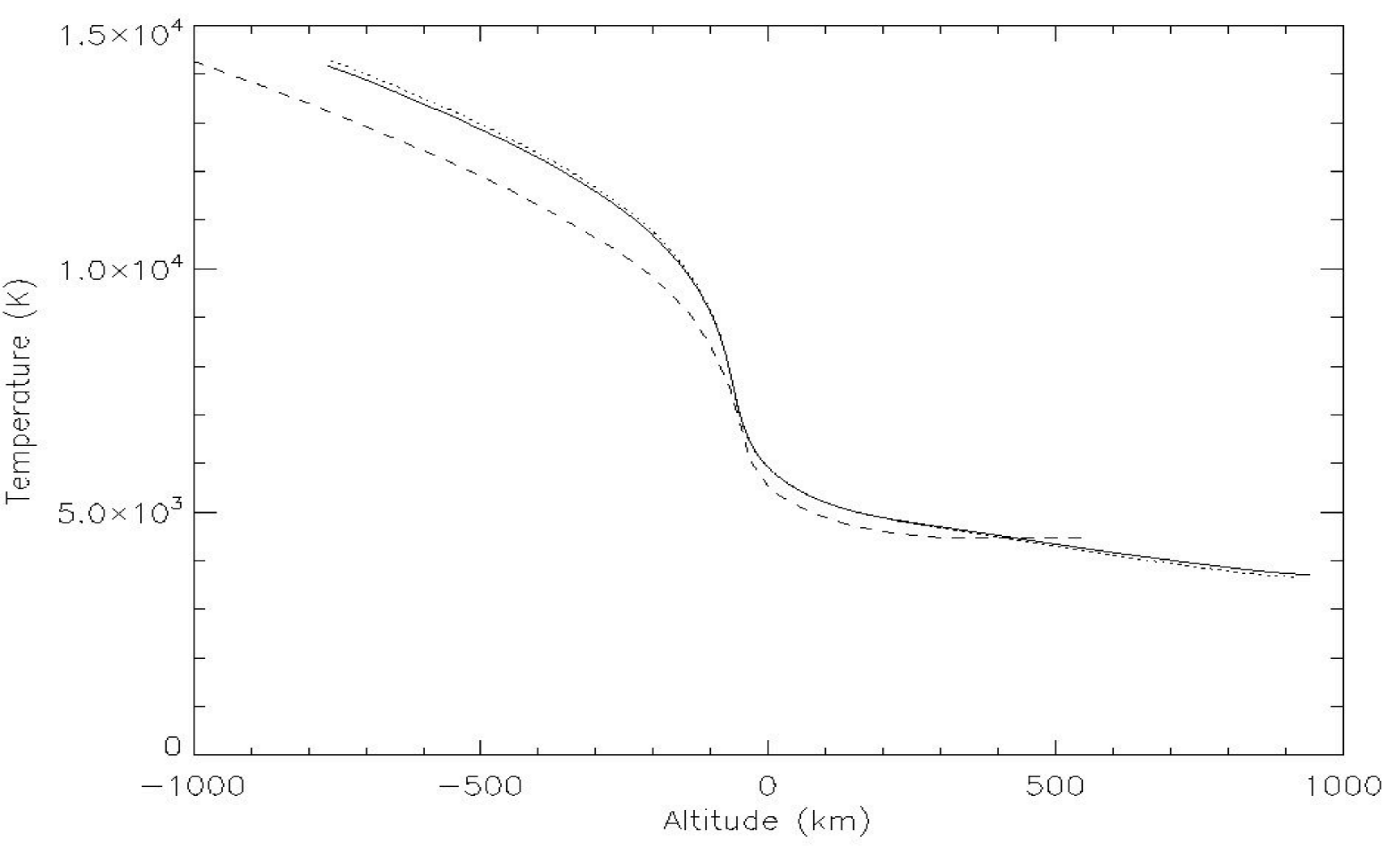
with B_h=20 kG at -20 Mm



63^3 during 1400 s
with B_h=300 G at -2.5 Mm

Ω=2.7 10^{-6} rad.s^{-1}
Θ=45 °

Atlas12 & Stagger codes comparisons



Optical depth 2/3 at altitude 0 km

Conclusion

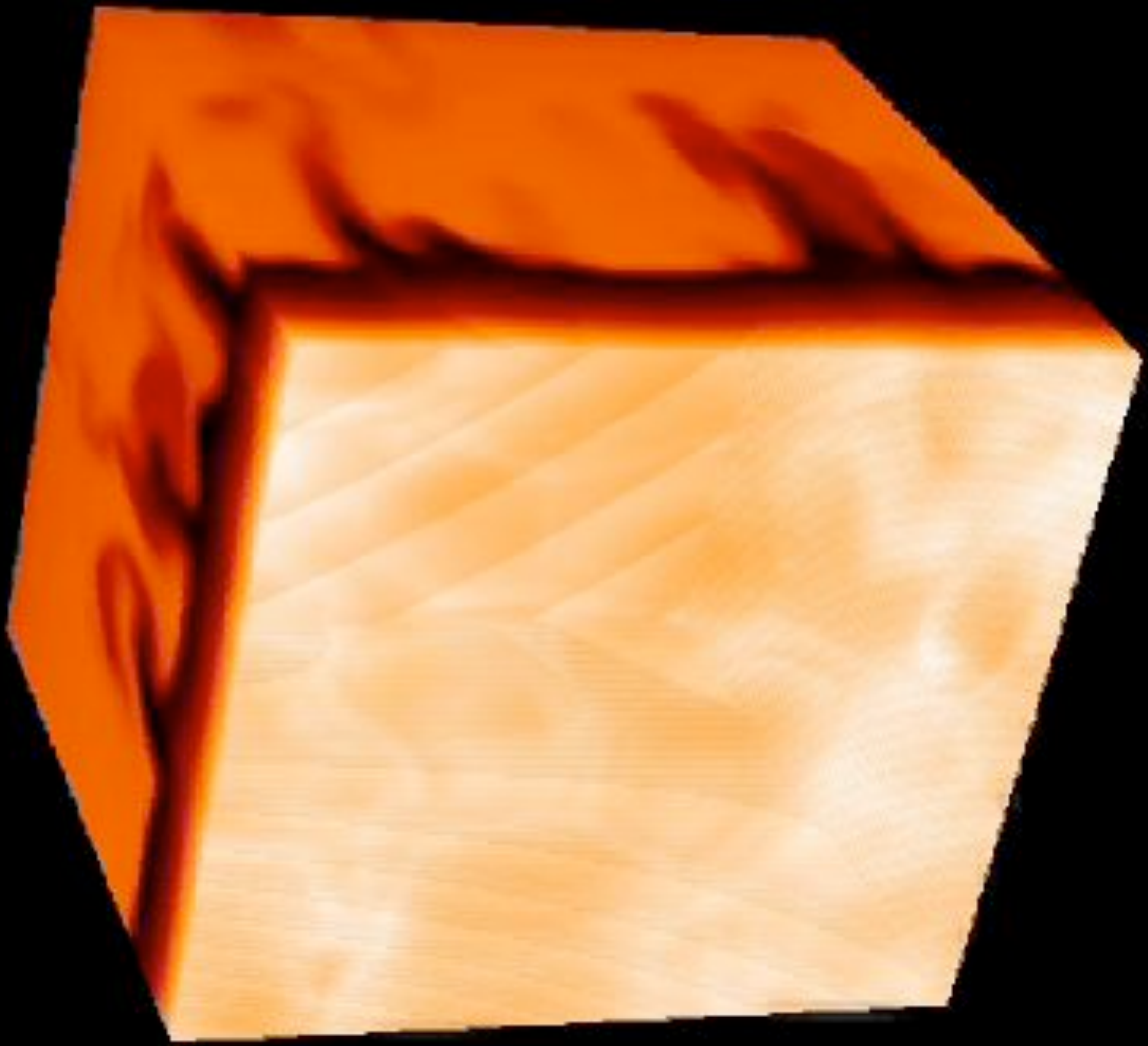
Atlas12 : 1D , accurate radiative transfer

Stagger : 3D, convection and magnetic evolution

Both codes relate surface observable quantities
to the interior

Stagger depends on Atlas12 and on lower boundary
conditions provided by other codes

STAGGER: example of entropy fluctuations



Atmosphere grids

Surface conditions are changed : Teff, log g

Composition is changed : N_H, N_{He} and
the metal fractions Z=3 to Z=99

T(τ), P(τ), relations, spectra etc... for :

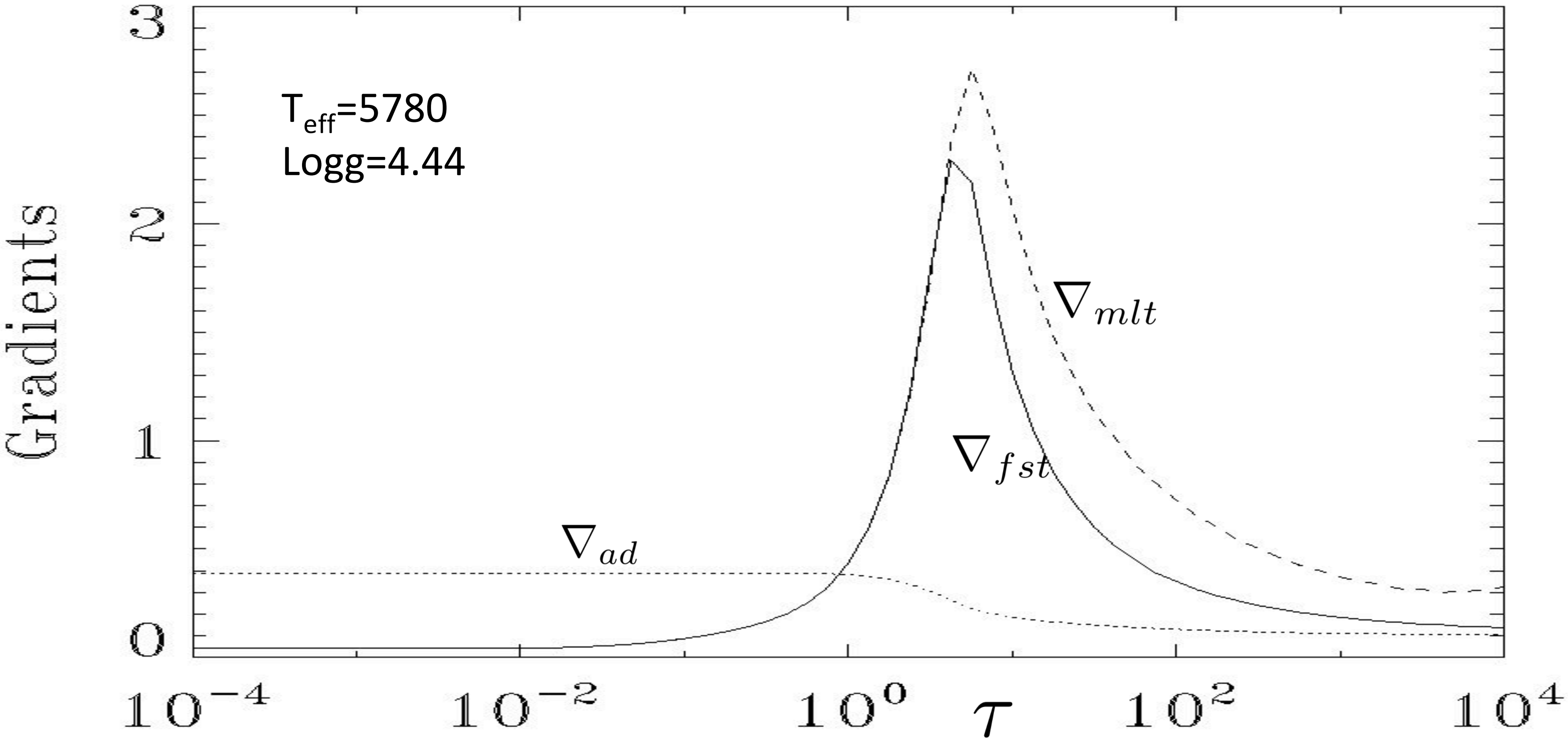
All the values of T_{eff} (4000K; 6400K) and log g (0.5; 5.5): 275 models

Solar compositions Asplund et al. (2005) et Asplund et al. (2009)
MLT and FST version of Canuto, Goldman, Mazzitelli (1996)

ATLAS12 code : Hα, Hβ profiles

Inefficient convection for τ ≤ 10

∇ Is close to ∇_{rad} Λ = 0.5 H_p is low

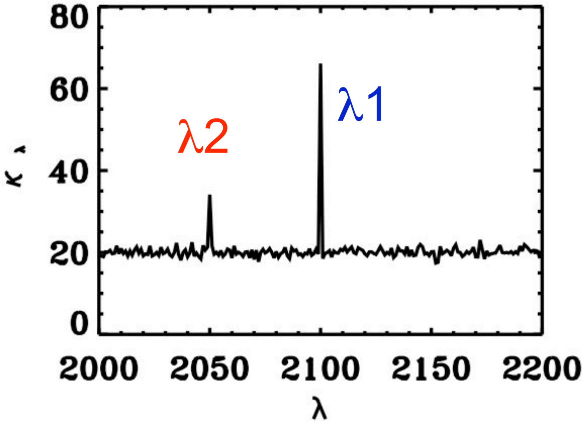


Groups method

4 non contiguous frequency groups corresponding to the same opacity regimes

Monochromatic opacities & 1D atmosphere model

⇒ Define the groups



If log $\tau_{\lambda 1}$=1 then log $\tau^* < -3$: heavy lines group

$\kappa = 10^3 \kappa^*$

If log $\tau_{\lambda 2}$=1 then $0 <$ log $\tau^* < -1$:

weak line group

$\kappa = 10^1 \kappa^*$

$$cos\theta \frac{dI_i}{\kappa_i \rho dz} = I_i - B_i$$

$$Q_{rad} = 4\pi\rho \sum_{i=1,4} \kappa_i (J_i - B_i)\Delta\nu_i$$

The data vary with X_i, T_{eff} and logg