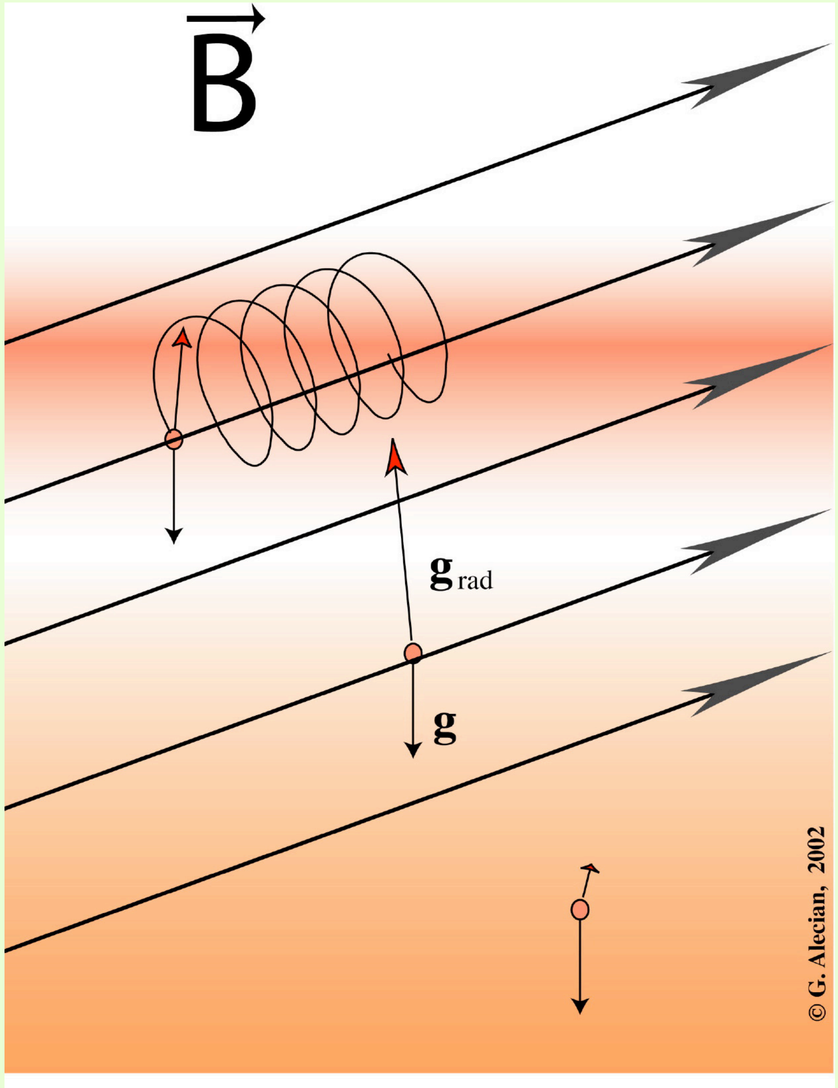
Diffusion in magnetic fields

G. Alecian

(CNRS, Observatoire de Paris)



Magnetic Ap star

Also:

-Ambipolar diffusion
(Babel & Michaud, 1991)

-Effect on models
(LeBlanc, Michaud & Babel, 1994)

Ion diffusion velocity without magnetic field

Microscopic diffusion velocity of an ion (Z_i) :

$$V_{Di} \approx D_{ip}\left[-\left(A_i - \frac{Z_i - 1}{2}\right)\frac{m_p}{kT}g + A_i\frac{m_p}{kT}g_i^{rad} + \ldots\right]$$

gravity

Radiative acceleration

The effect of horizontal magnetic fields on the diffusion velocity

- Correcting factor in the direction orthogonal to magnetic lines

$$f_{slow,i} = \left(1 + \omega_i^2 t_i^2\right)^{-1}$$

$$0 < f_{slow,i} \le 1$$

t_i is the « collision » time

$\omega_i / 2\pi$ is the cyclotron frequency

$$\omega_i = \frac{ZeH}{m_i c}$$

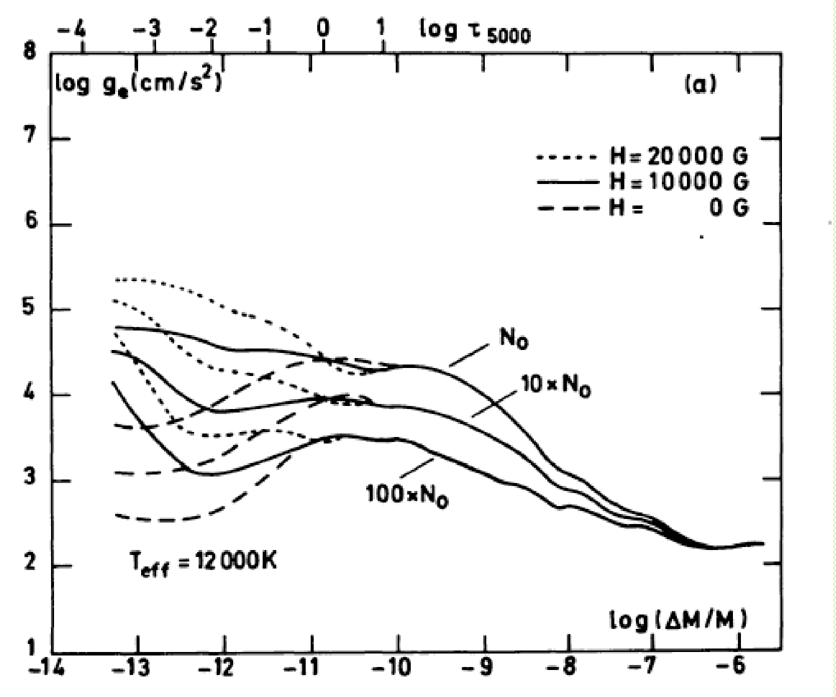
- The corrected average diffusion velocity (approximated) for horizontal field

$$V_D \approx \frac{\sum_i N_i f_{slow,i} V_{Di}}{\sum_i N_i}$$

Some typical results

- **Silicon**: Vauclair, Hardorp & Peterson (1979) have shown the consequence of the ions trapping by the magnetic field

Fig4a of Alecian & Vauclair (1981)



Similar studies for:

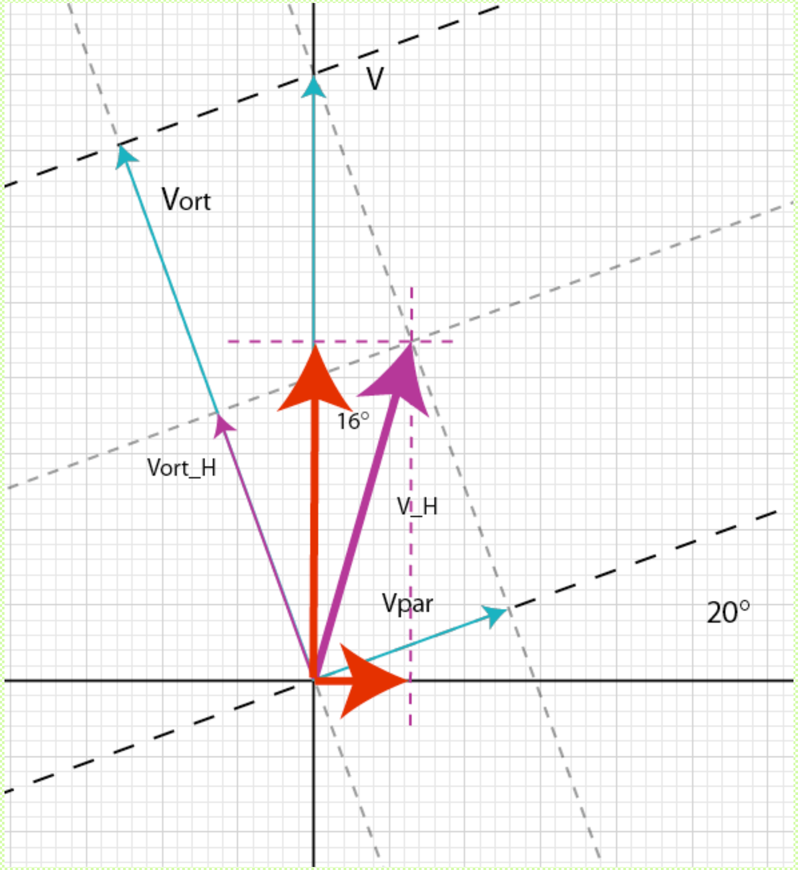
- **Oblique rotator** model (Michaud, Megessier & Charland, 1981)

- **Ga** in Ap stars (Alecian & Artru, 1987)

- **Ca, Sc, Ti, Mn, Cr, Sr** in 53 Camelopardalis (Babel & Michaud, 1991)

- **Al** in Ap stars (Hui Bon Hoa, Alecian & Artru, 1996)

Oblique magnetic lines



Alecian & Vauclair, 1981 :

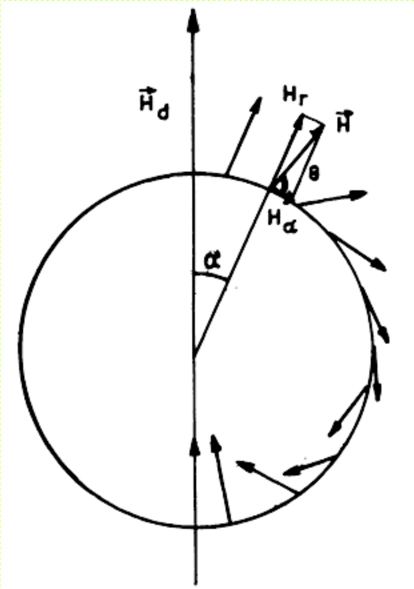
$$V_{H,Zi} = V_i\left(f_{slow,i} + \frac{1}{f_{slow,i}}\sin^2\theta\right)$$

and,
an horizontal component!

$$V_{H,Xi} = \frac{f_{slow,i}V_i}{2}\sin 2\theta$$

Horizontal diffusion !

- Mégessier, 1984 (Si distribution on Bp and Ap stars with dipolar field and applying the previous formulae)



However, the time scale for the appearance of significant inhomogeneities through horizontal diffusion onto the stellar surface is about **10^7y** !

This implies that magnetic structures should be stable over a long period. Moreover, time scales are much shorter for vertical diffusion, which remains dominant in the stratification process

Therefore, abundance patches are more likely formed through the V_z component (by inhomogeneous vertical diffusion according to the local field angle).

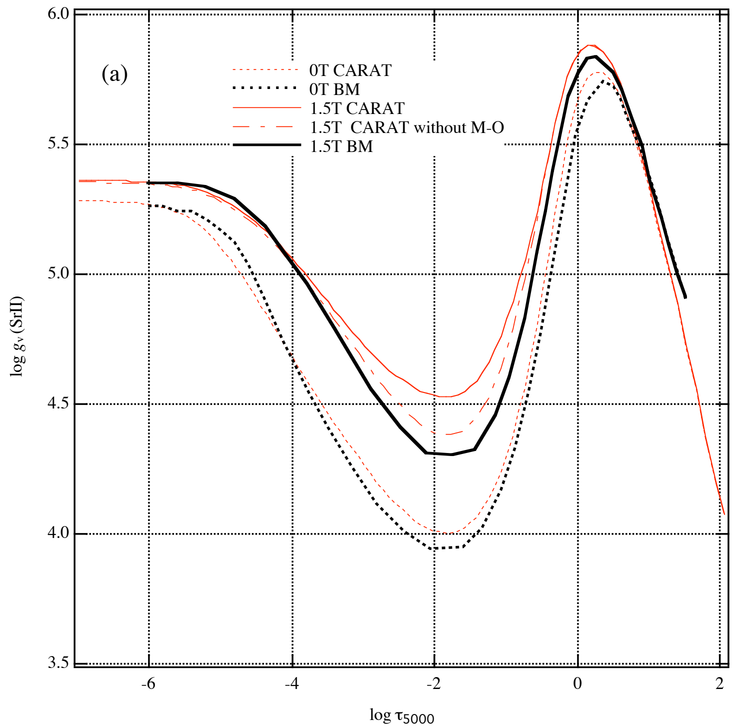
Radiative accelerations, with and without magnetic field

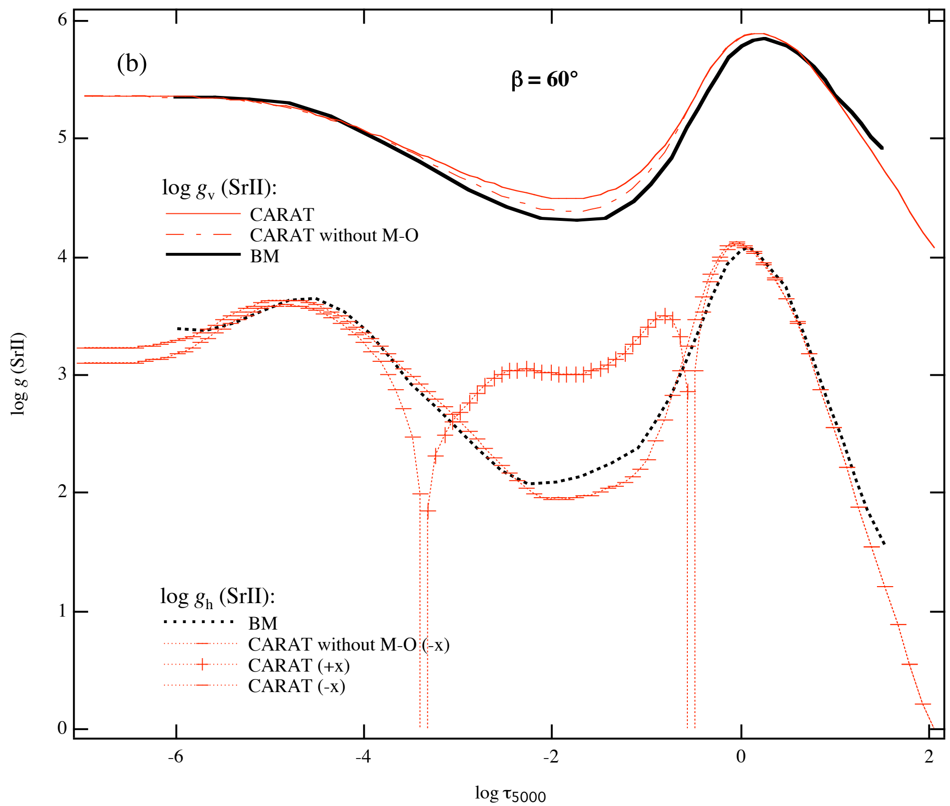
$$g_i^{rad} = \sum_{k,m>k} \frac{n_{i,k}}{n_i A m_p c} \int_0^\infty \sigma_{k,m}\, \phi(\nu, n_i)\, \mathrm{d}\nu$$

$$\mathbf{g}_\mathbf{i}^\mathbf{rad} = \sum_{k,m>k} \frac{n_{i,k}}{n_i A m_p c} \int_\nu \int_\Omega (\mathbf{e}.\mathbf{I})\, \Omega\, \mathrm{d}\Omega \mathrm{d}\nu$$ (magnetic)

The CARAT code

- Polarized radiation transfer in LTE (Alecian & Stift, 2004)
  - VALD data base, Kurucz ATLAS9 models, plane-parallel
  - Magnetic field up to 60 000 Gauss, any angle
  - Detailed opacities up to 5 mA of resolution
  - radiative accelerations for 329 ions
  - parallel computing

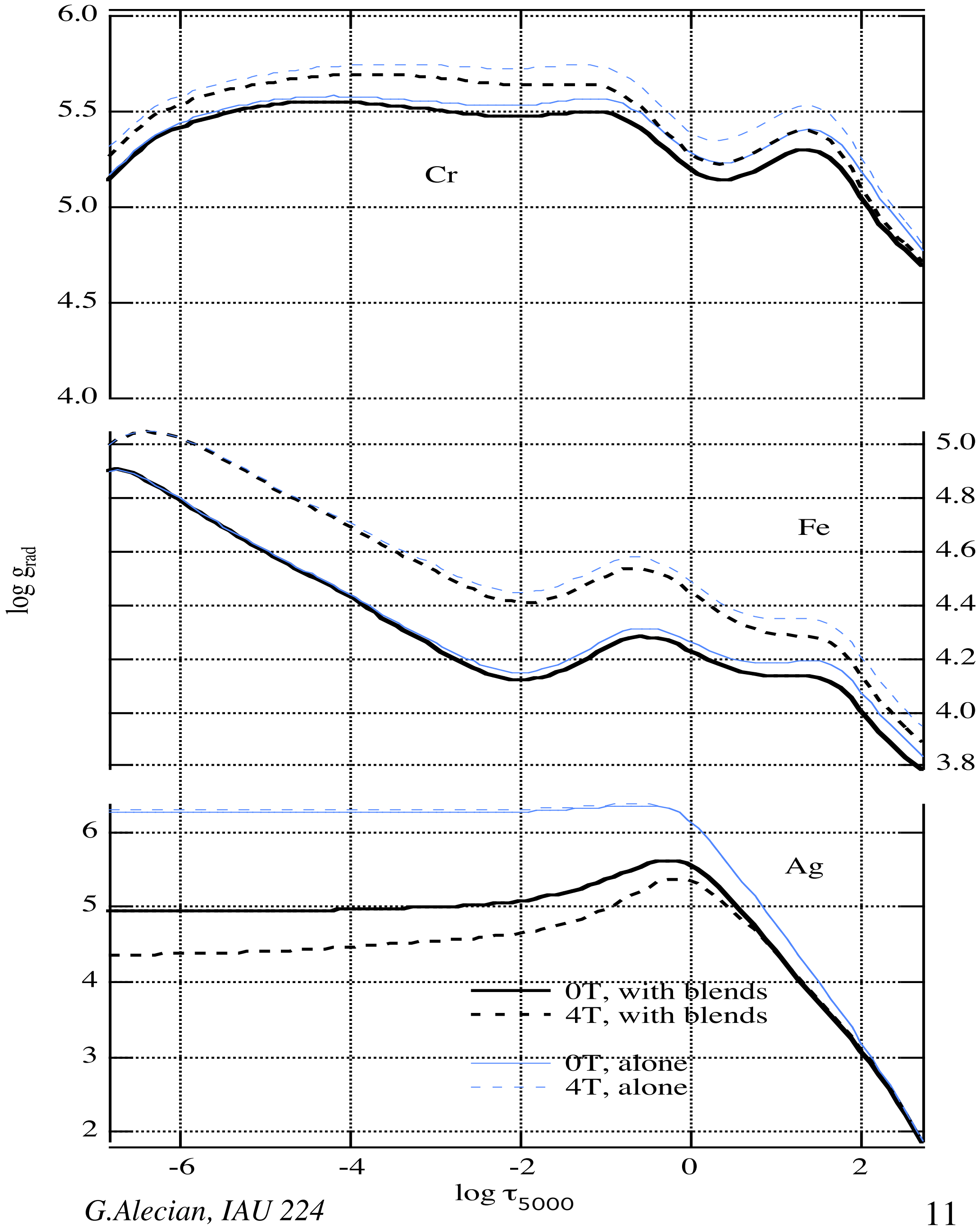




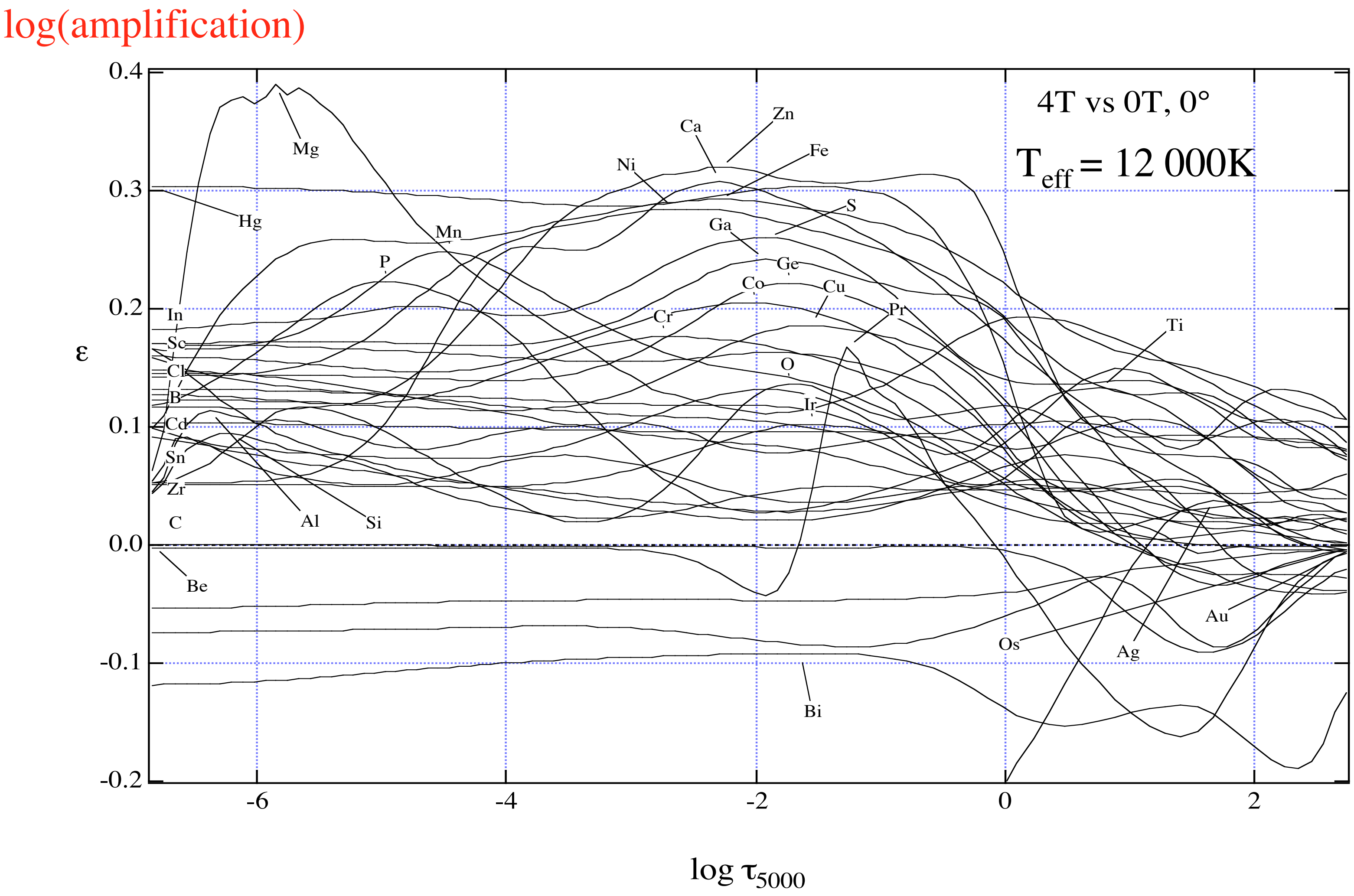
SrII λ 4077

T_{eff}=8500K

Effect of Blends



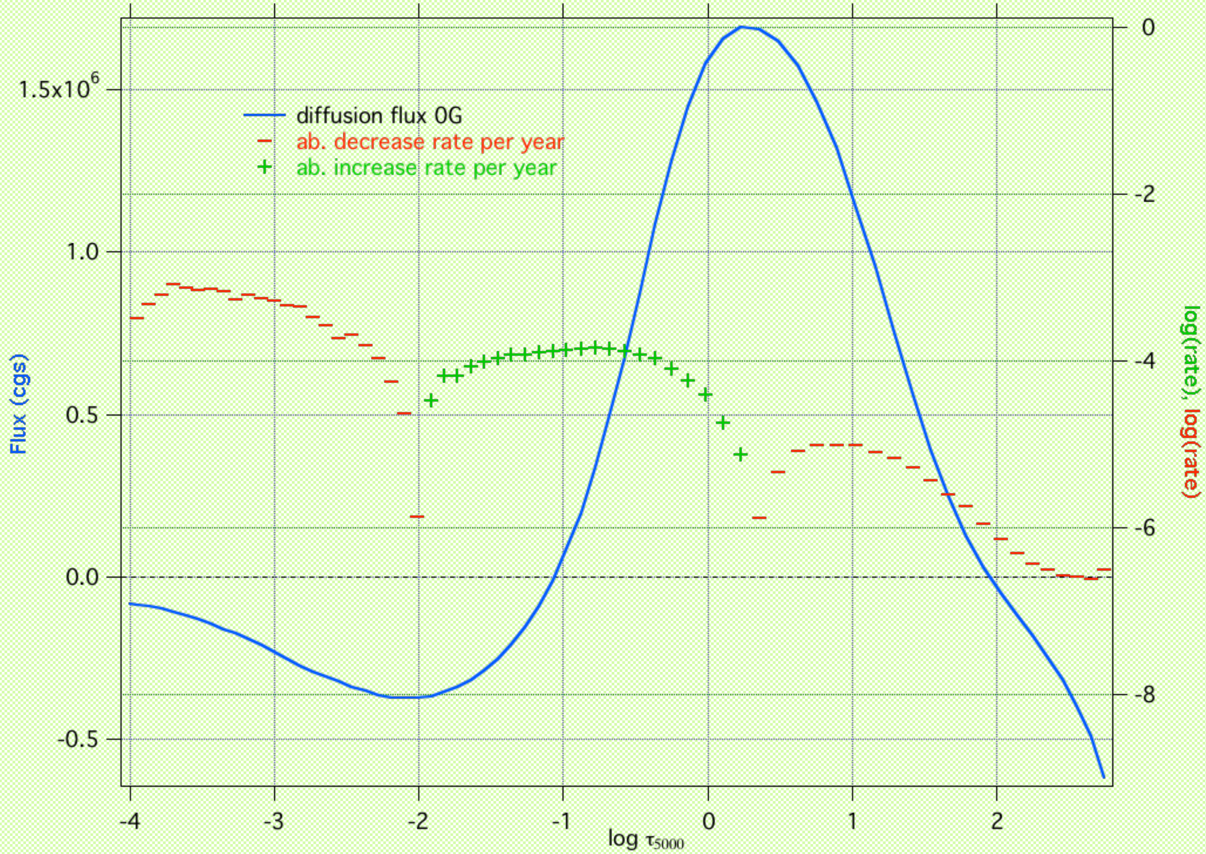
Zeeman amplification



Preliminary results (complete computation with CARAT)

Al

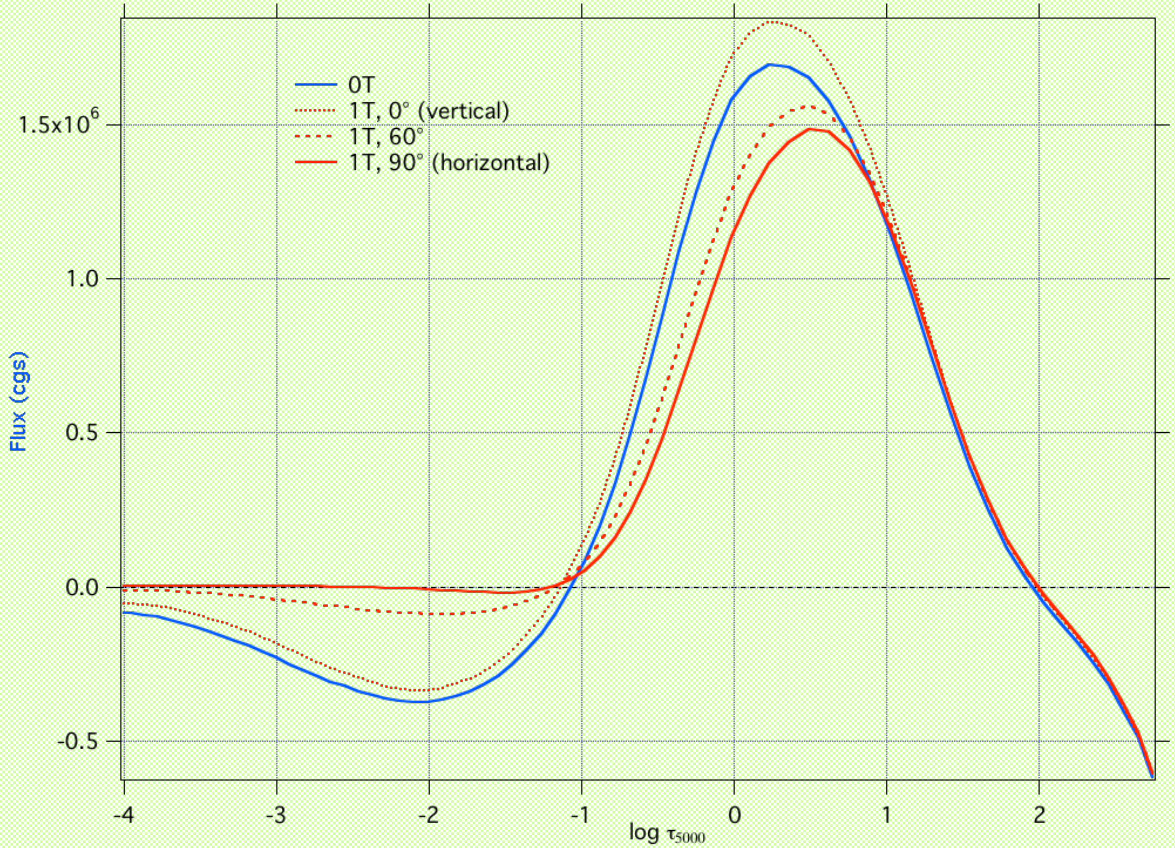
T_{eff}=12000K



Preliminary results (2)

Al

comparing fluxes



Future developments

- Stratification at equilibrium (already in progress for zero field case, see LeBlanc et al.)
  - ➔ **Self-consistent models**
  - ➔ **NLTE**
- 2D stratifications (modelling oblique rotators)
- + all potentially important processes (ambipolar diffusion, hydrodynamics,…)
- Connection to internal structure
- Far in the future: time-dependent stratifications (LTE,…)