The art of Stokes inversions

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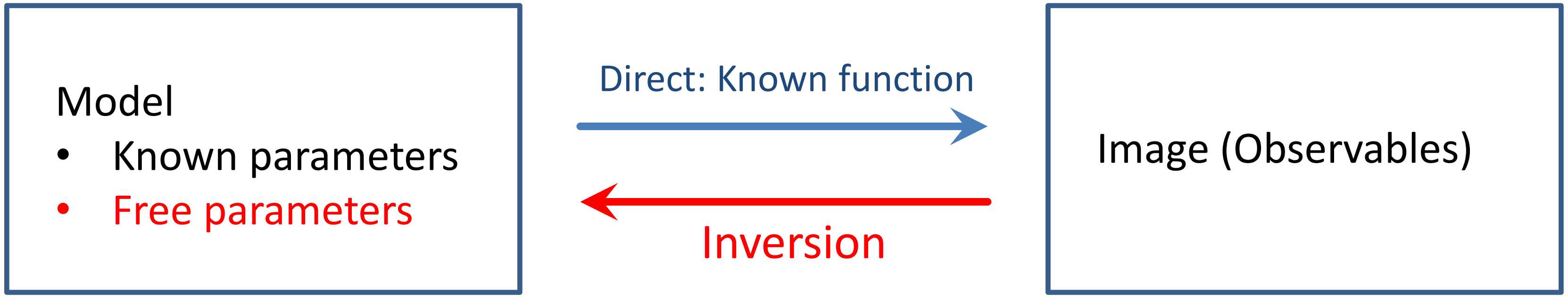
Inversion techniques, or Inversion methods are numerical tools that allow us to infer some free parameters of a model from an image



Inverse Problems (1995) Vol 11, number 4 : *Inverse Problems in Astronomy*
Inverse Problems in Astronomy (1986) Craig & Brown CRC Press

- The first paper: Victor Ambartsumian (1929) Zeitschrift für Physik 53, 690
- Goncharskiy, Cherepashchuk and Yagola (1978) *Numerical methods of solving inverse problems in astrophysics*

Solar Physics
- Helioseismology
- Spectropolarimetry (Inversion of RTE for polarized light)

Outline

PART 1: Theory

1. The RTE: formal solution & approximations
2. The Response Functions
3. What is an inversion technique? How does it work?
4. The SIR code.
5. How to choose an inversion technique?
6. Running SIR

PART 2: SIR exercises

Download

Download SIR code from:
https://github.com/BasilioRuiz/SIR-code

And these slides and exercises from:
https://github.com/BasilioRuiz/SIR-course

1: The RTE: formal solution & approximations

RTE: $$\frac{dI_\nu}{ds} = -\chi_\nu I_\nu + \eta_\nu$$

1: The RTE: formal solution & approximations

RTE: $$\frac{dI_\nu}{ds} = -\chi_\nu I_\nu + \eta_\nu$$

Absorption coefficient: $$\chi_\nu = \underbrace{(\chi_{ff} + \chi_{bf})}_{\chi_c} + \chi_{bb}\,\phi(\nu)$$

Emission: $$\eta_\nu$$

Optical depth: $$d\tau_\nu = -\chi_\nu\, ds$$

Continuum optical depth: $$d\tau_c = -\chi_c\, ds$$

Suppose no emission :

1: The RTE: formal solution & approximations

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Continuum optical depth: $$d\tau_c = -\chi_c\, ds$$

Suppose no emission : $$\frac{dI_\nu}{ds} = -\chi_\nu I_\nu \longrightarrow \quad I_\nu = I_0 e^{-\int_0 \chi_\nu ds} = I_0 e^{-\Delta s/\bar{l}}$$

1: The RTE: formal solution & approximations

RTE: $$\frac{dI_\nu}{ds} = -\chi_\nu I_\nu + \eta_\nu$$

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Emission: $$\eta_\nu$$

Optical depth: $d\tau_\nu = -\chi_\nu\, ds$ (number of mean free paths at ν)

Continuum optical depth: $d\tau_c = -\chi_c\, ds$ (number of mean free paths at continuum)

Suppose no emission : $$\frac{dI_\nu}{ds} = -\chi_\nu I_\nu \longrightarrow \quad I_\nu = I_0 e^{-\int_0 \chi_\nu ds} = I_0 e^{-\Delta s / \bar{l}}$$

1: The RTE: formal solution & approximations

RTE:

$$\frac{dI_\nu}{ds} = -\chi_\nu I_\nu + \eta_\nu$$

Continuum optical depth: $d\tau_c = -\chi_c \, ds$

$$\frac{dI_\nu}{d\tau_c} = \frac{\chi_\nu}{\chi_c} I_\nu - \frac{\eta_\nu}{\chi_c}$$

1: The RTE: formal solution & approximations

RTE:

$$\frac{dI_\nu}{ds} = -\chi_\nu I_\nu + \eta_\nu$$

Continuum optical depth: $d\tau_c = -\chi_c \, ds$

$$\frac{dI_\nu}{d\tau_c} = \frac{\chi_\nu}{\chi_c} I_\nu - \frac{\eta_\nu}{\chi_c} = \frac{\chi_\nu}{\chi_c}\left(I_\nu - \frac{\eta_\nu}{\chi_\nu} \right)$$

1: The RTE: formal solution & approximations

RTE: $$\frac{dI_\nu}{ds} = -\chi_\nu I_\nu + \eta_\nu$$

Continuum optical depth: $d\tau_c = -\chi_c\, ds$

$$\frac{dI_\nu}{d\tau_c} = \frac{\chi_\nu}{\chi_c} I_\nu - \frac{\eta_\nu}{\chi_c} = \frac{\chi_\nu}{\chi_c}\left(I_\nu - \frac{\eta_\nu}{\chi_\nu} \right) = \kappa \left(I_\nu - S_\nu \right)$$

S_ν

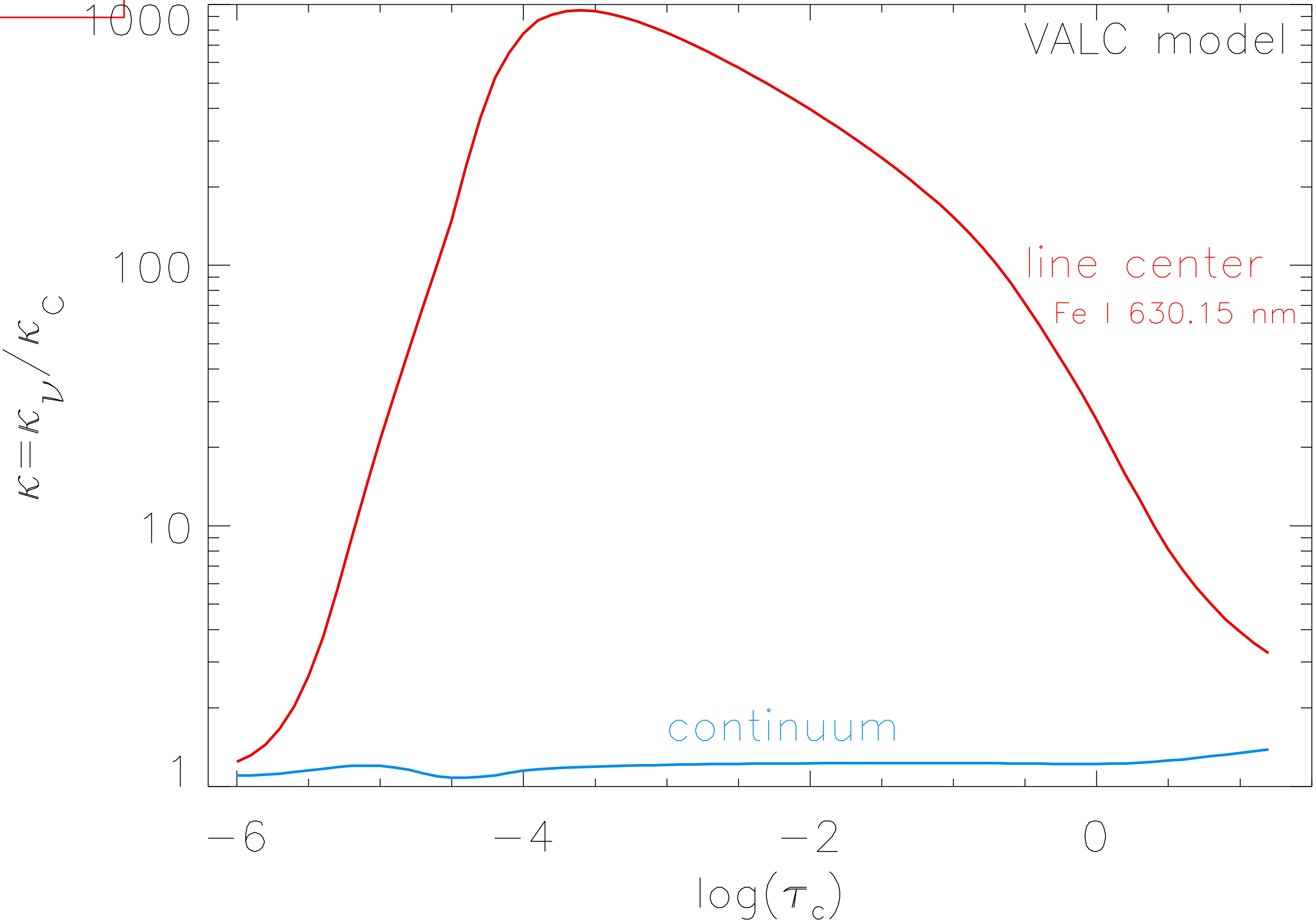
per cm cm²/ g

$$\chi_\nu = \kappa_\nu \rho$$
$$\chi_c = \kappa_c \rho$$

$$\frac{\chi_\nu}{\chi_c} = \frac{\kappa_\nu}{\kappa_c} = \kappa$$

1: The RTE: formal solution & approximations

$$\frac{dI_\nu}{d\tau_c} = \kappa\left(I_\nu - S_\nu\right)$$



1: The RTE: formal solution & approximations

$$\boxed{\frac{dI_\nu}{d\tau_c} = \kappa\left(I_\nu - S_\nu\right)}$$

Formal solution: integration factor O

$$\frac{d(OI_\nu)}{d\tau_c} = \frac{dO}{d\tau_c} I_\nu + O\frac{dI_\nu}{d\tau_c} = \frac{dO}{d\tau_c} I_\nu + O\kappa\left(I_\nu - S_\nu\right)$$

$$\frac{dO}{d\tau_c} \equiv -O\kappa$$

$$\frac{d(OI_\nu)}{d\tau_c} = -O\kappa S_\nu$$

$$I_\nu(\tau_1) = O^{-1}(\tau_1)O(\tau_0)I_\nu(\tau_0) - \int_{\tau_0}^{\tau_1} O^{-1}(\tau_1)O(\tau_c)\kappa S d\tau_c$$

1: The RTE: formal solution & approximations

$$\boxed{\frac{dI_\nu}{d\tau_c} = \kappa\left(I_\nu - S_\nu\right)}$$

Formal solution: integration factor O

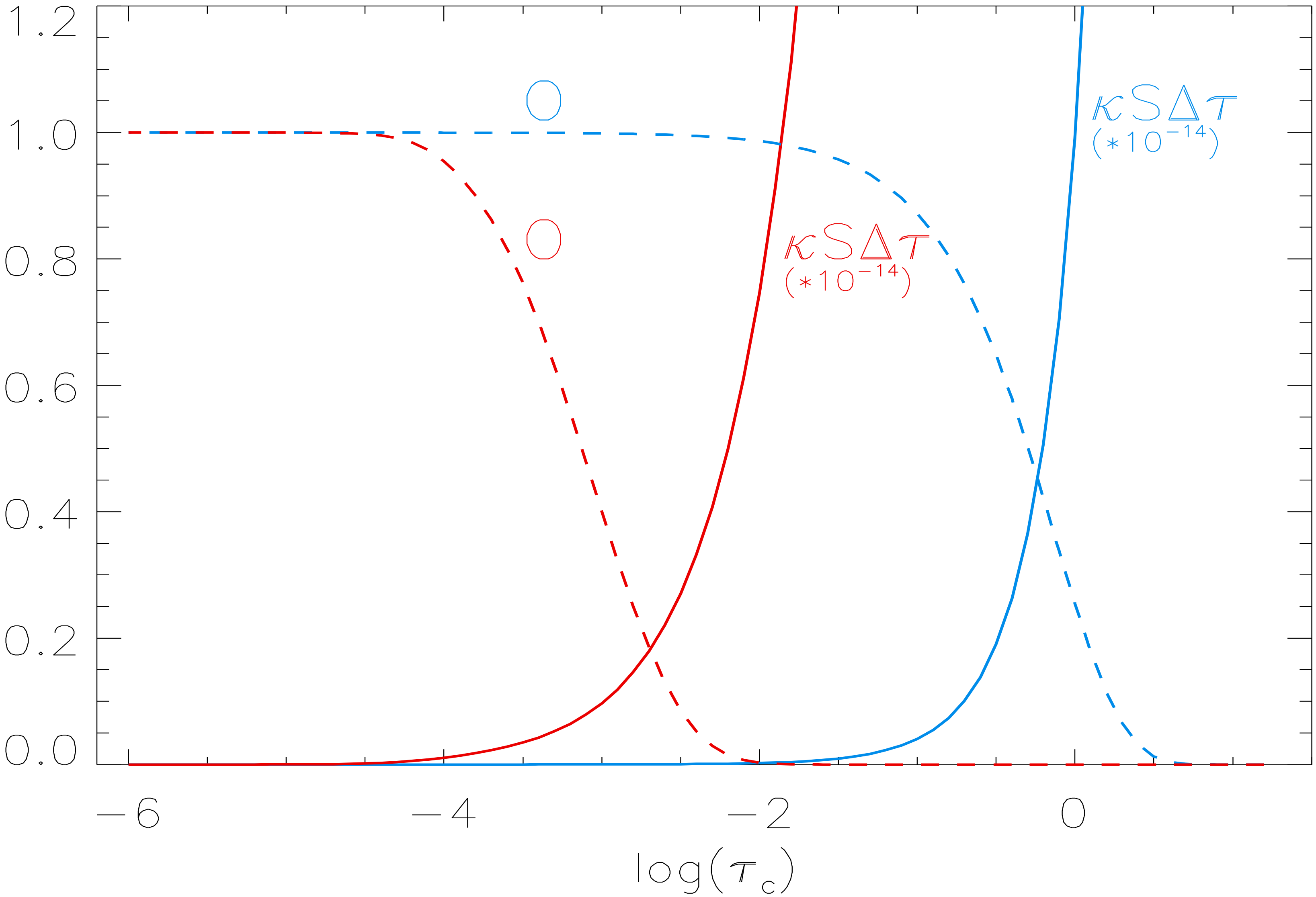
$$\frac{d(OI_\nu)}{d\tau_c} = \frac{dO}{d\tau_c} I_\nu + O\frac{dI_\nu}{d\tau_c} = \frac{dO}{d\tau_c} I_\nu + O\kappa\left(I_\nu - S_\nu\right)$$

$$\frac{dO}{d\tau_c} \equiv -O\kappa \qquad \boxed{O(\tau) = e^{-\int_0^\tau \kappa d\tau}} \qquad \frac{d(OI_\nu)}{d\tau_c} = -O\kappa S_\nu$$

$$\boxed{I_\nu = O(\tau_0) I_\nu(\tau_0) + \int_0^{\tau_0} O(\tau_c)\kappa S_\nu d\tau_c}$$

1: The RTE: formal solution & approximations

$$I_\nu = O(\tau_0) I_\nu(\tau_0) + \int_0^{\tau_0} O(\tau_c) \kappa S d\tau_c$$



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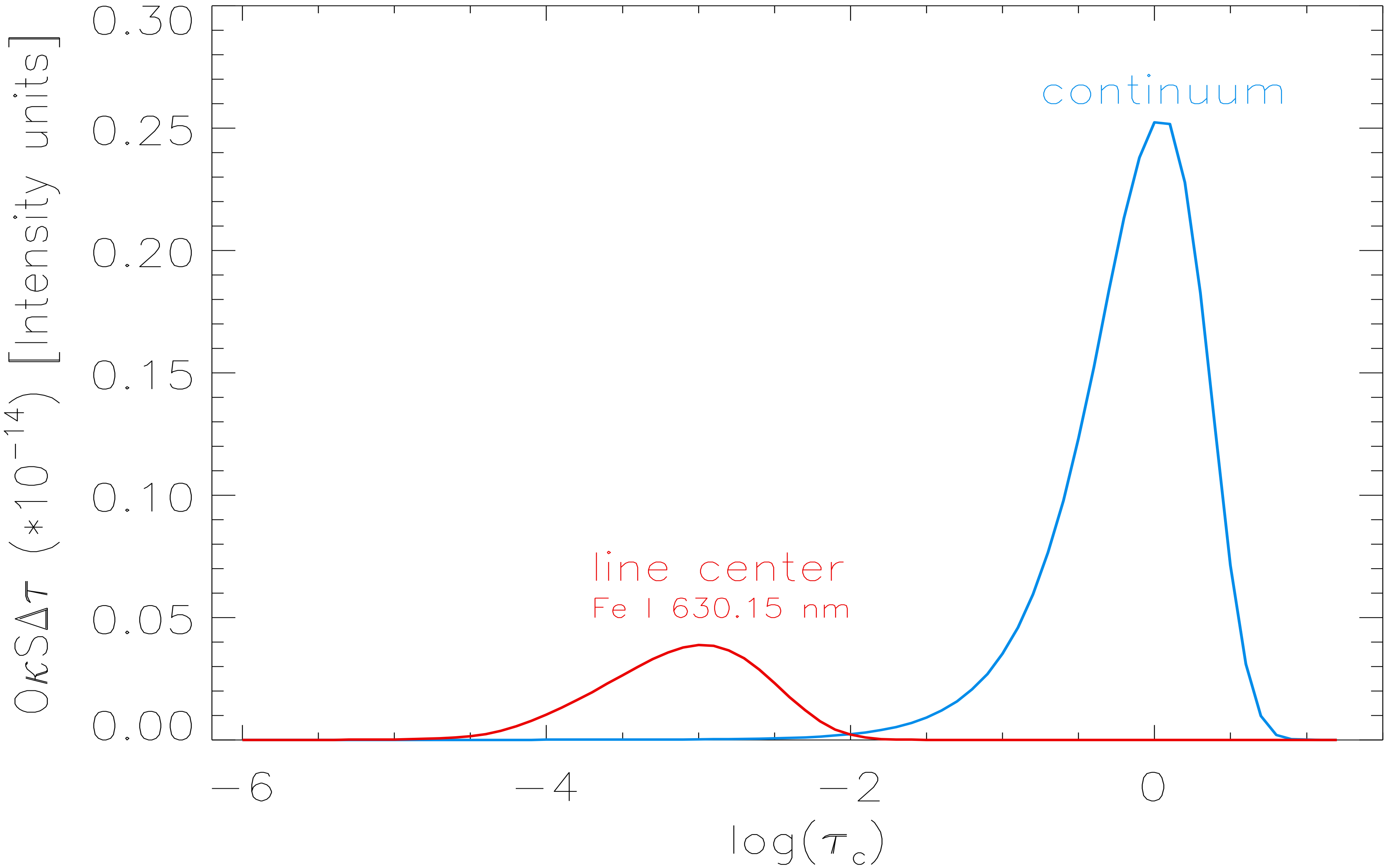
$$I_\nu = O(\tau_0) I_\nu(\tau_0) + \int_0^{\tau_0} O(\tau_c) \kappa S d\tau_c$$



1: The RTE: formal solution & approximations

$$I_\nu = O(\tau_0) I_\nu(\tau_0) + \int_0^{\tau_0} O(\tau_c) \kappa S d\tau_c$$

$\kappa(\tau), S_\nu(\tau)$ depend on the atomic populations n=n[T, P, $I_\nu(\tau)$)] $\longrightarrow$ SE equations

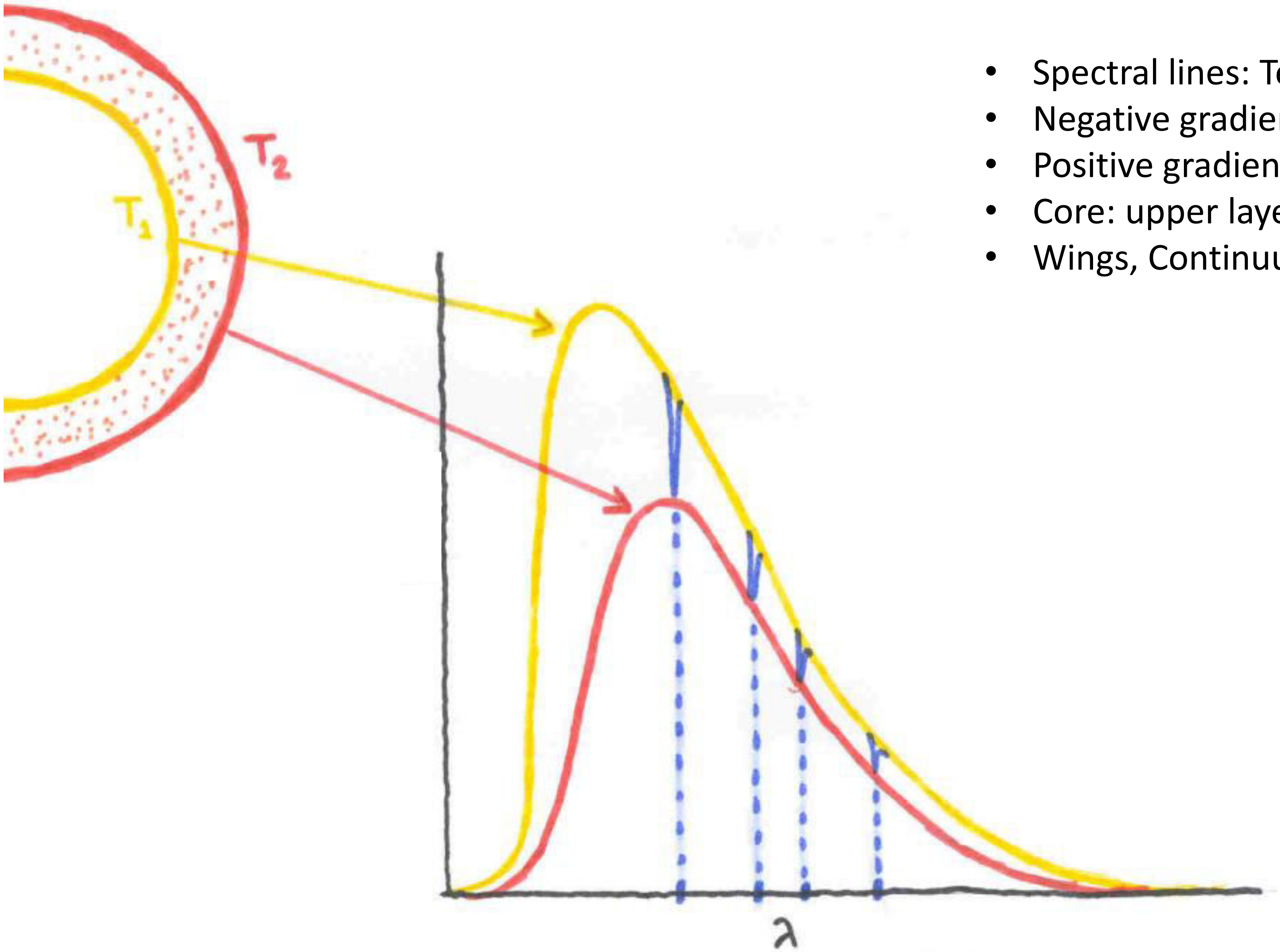
Some possible approximations:

- LTE: n=n[T, P] $\longrightarrow$ $\kappa[T(\tau), P(\tau)]$ & $S_\nu = B_\nu[T(\tau)]$
- Milne- Eddington (ME) approximation: $\kappa(\tau)$ =cte, $S_\nu(\tau) = S_0 + S_1\tau$

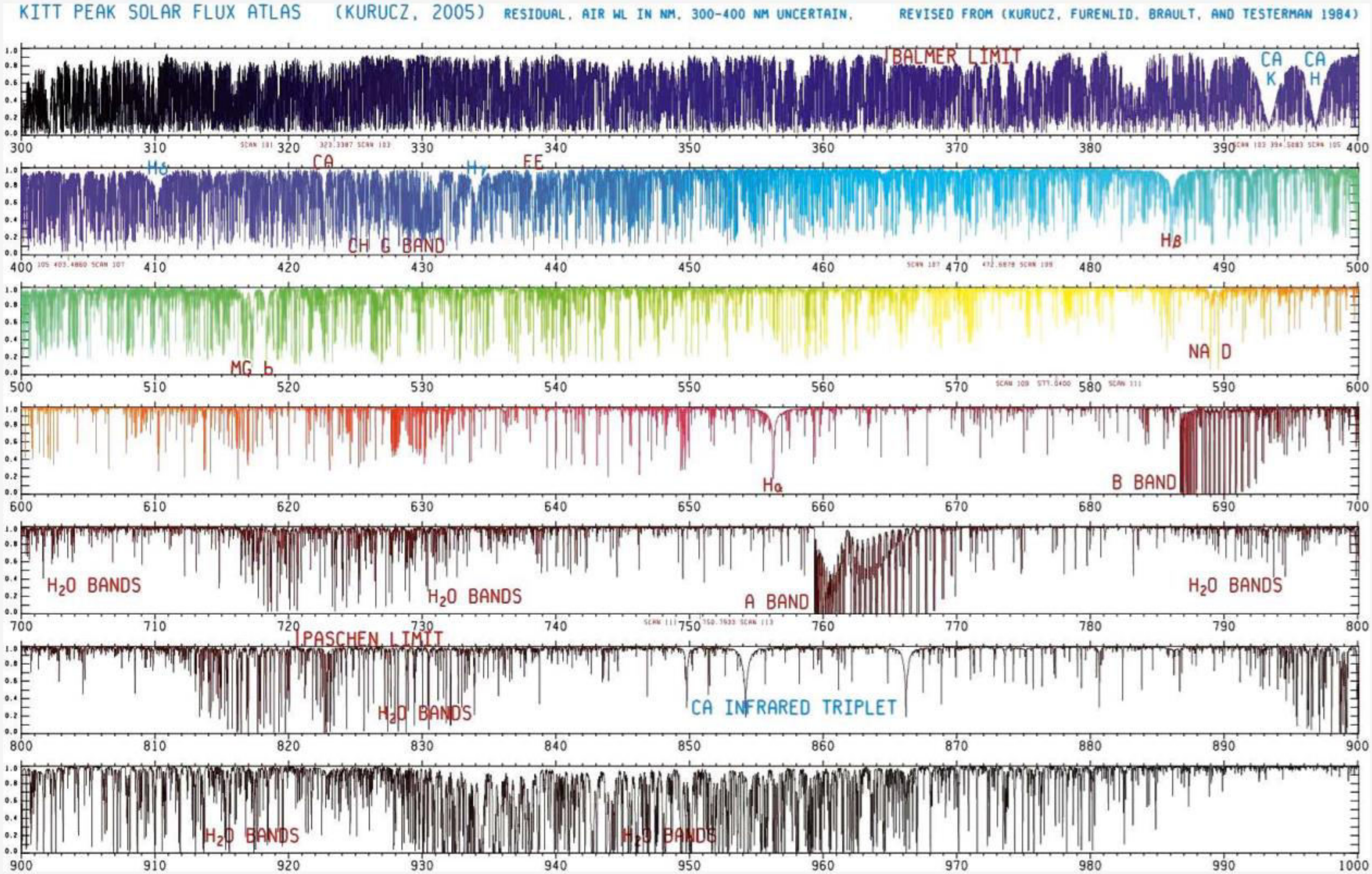
$$I_\nu(\tau_\nu = 0) = S_\nu(\tau_\nu = 1)$$

1: The RTE: formal solution & approximations

$$I_\nu(\tau_\nu = 0) = S_\nu(\tau_\nu = 1) \cong B_\nu[T(\tau_\nu = 1)]$$

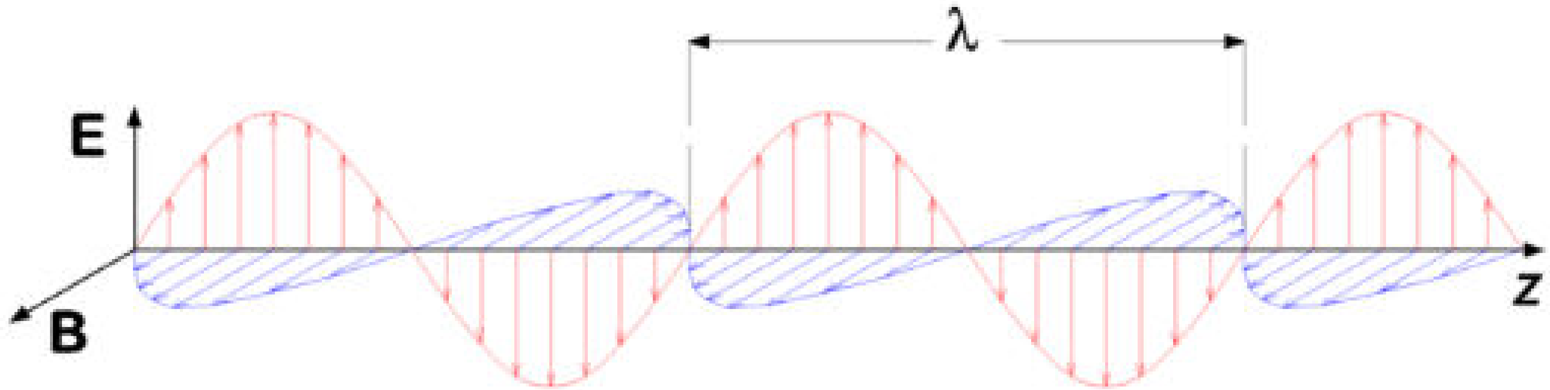


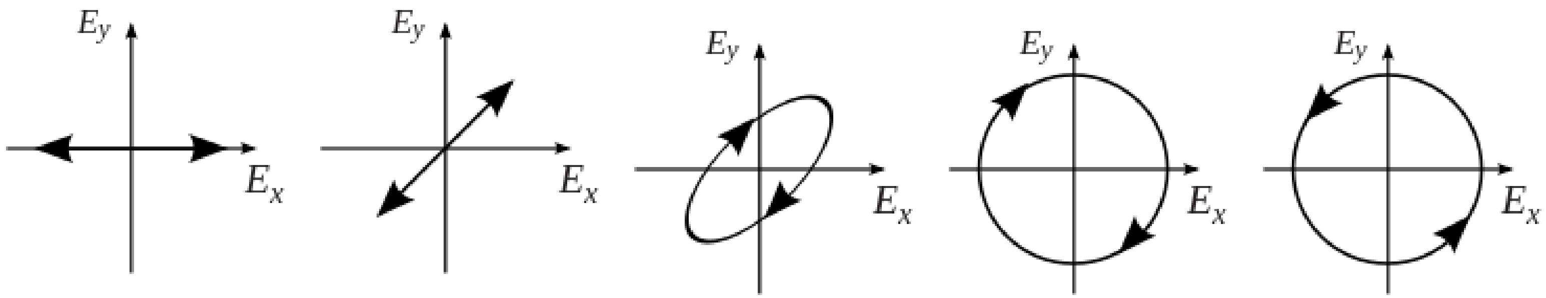
- Spectral lines: Temperature gradient
- Negative gradient: absorption lines
- Positive gradient: emission lines
- Core: upper layers
- Wings, Continuum: deeper layers



KITT PEAK SOLAR FLUX ATLAS (KURUCZ, 2005) RESIDUAL, AIR WL IN NM, 300-400 NM UNCERTAIN, REVISED FROM (KURUCZ, FURENLID, BRAULT, AND TESTERMAN 1984)
BALMER LIMIT
CA K
CA H
Hδ
CA
Hγ
FE
CH G BAND
Hβ
MG b
NA D
Hα
B BAND
H2O BANDS
A BAND
PASCHEN LIMIT
CA INFRARED TRIPLET

1: The RTE: formal solution & approximations





$$I = \updownarrow + \leftrightarrow$$

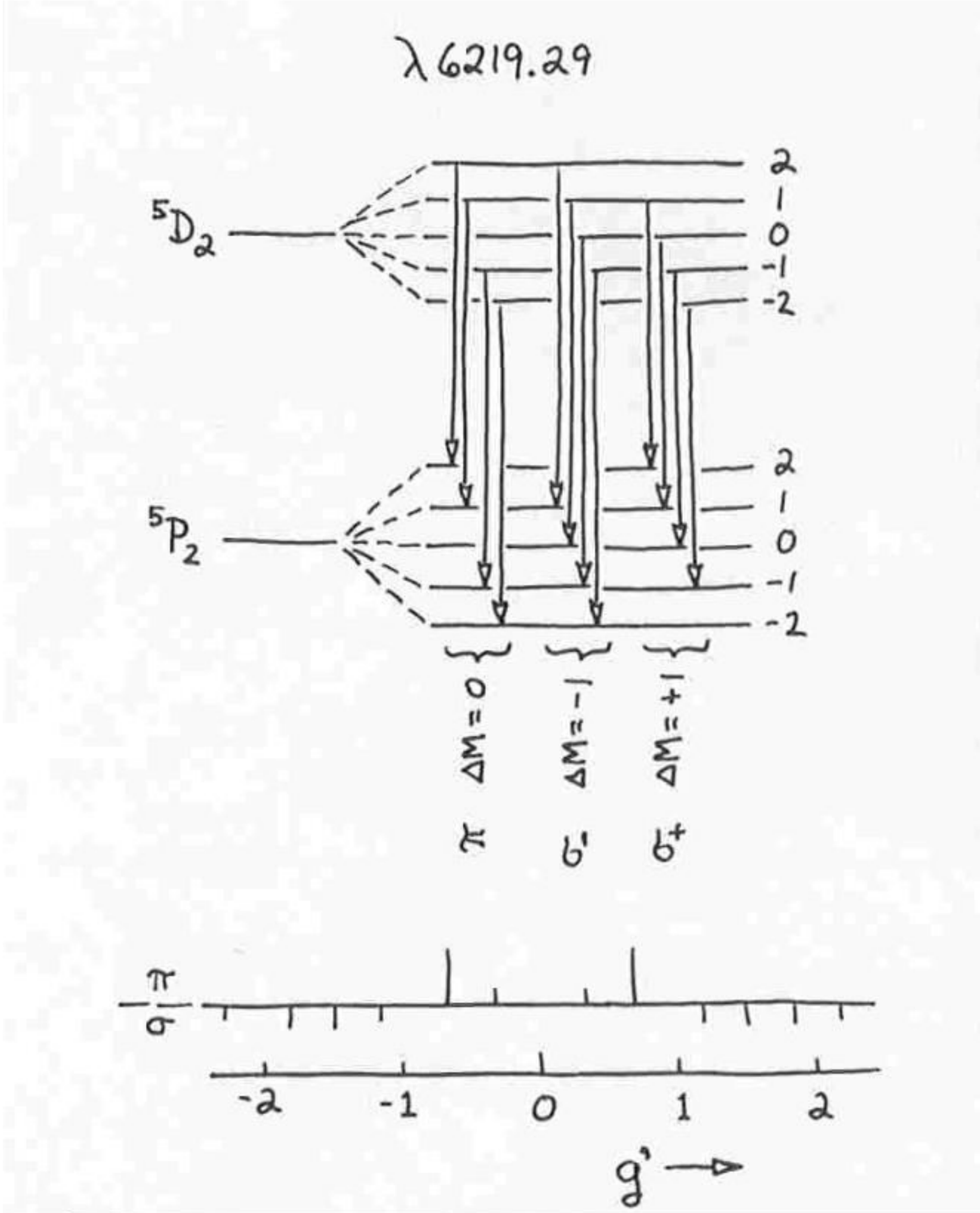
$$Q = \updownarrow - \leftrightarrow$$

$$U = \swarrow\!\!\!\nearrow - \nwarrow\!\!\!\searrow$$

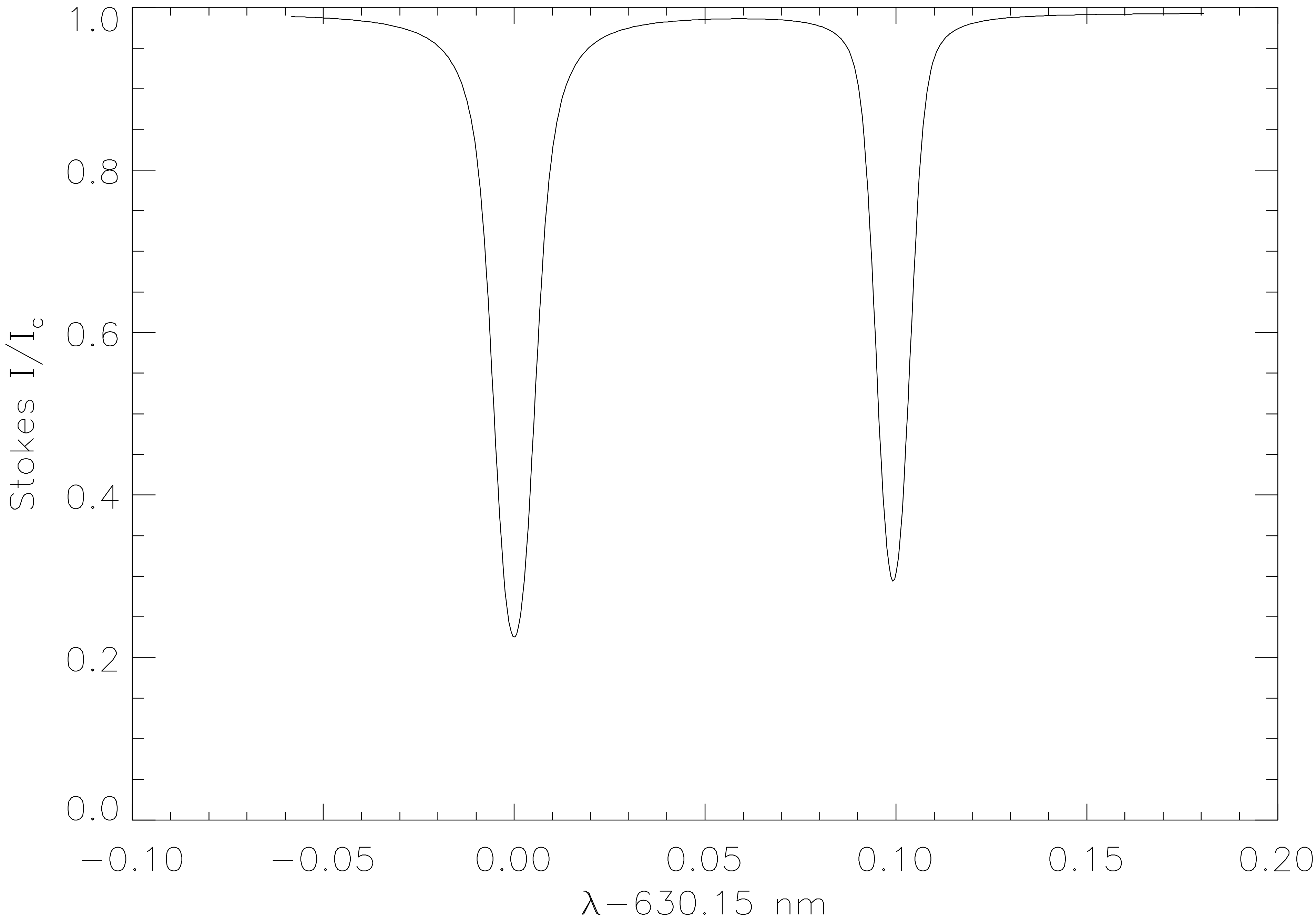
$$V = \circlearrowleft - \circlearrowright$$

1: The RTE: formal solution & approximations

Pieter Zeeman (1865-1943)



1: The RTE: formal solution & approximations



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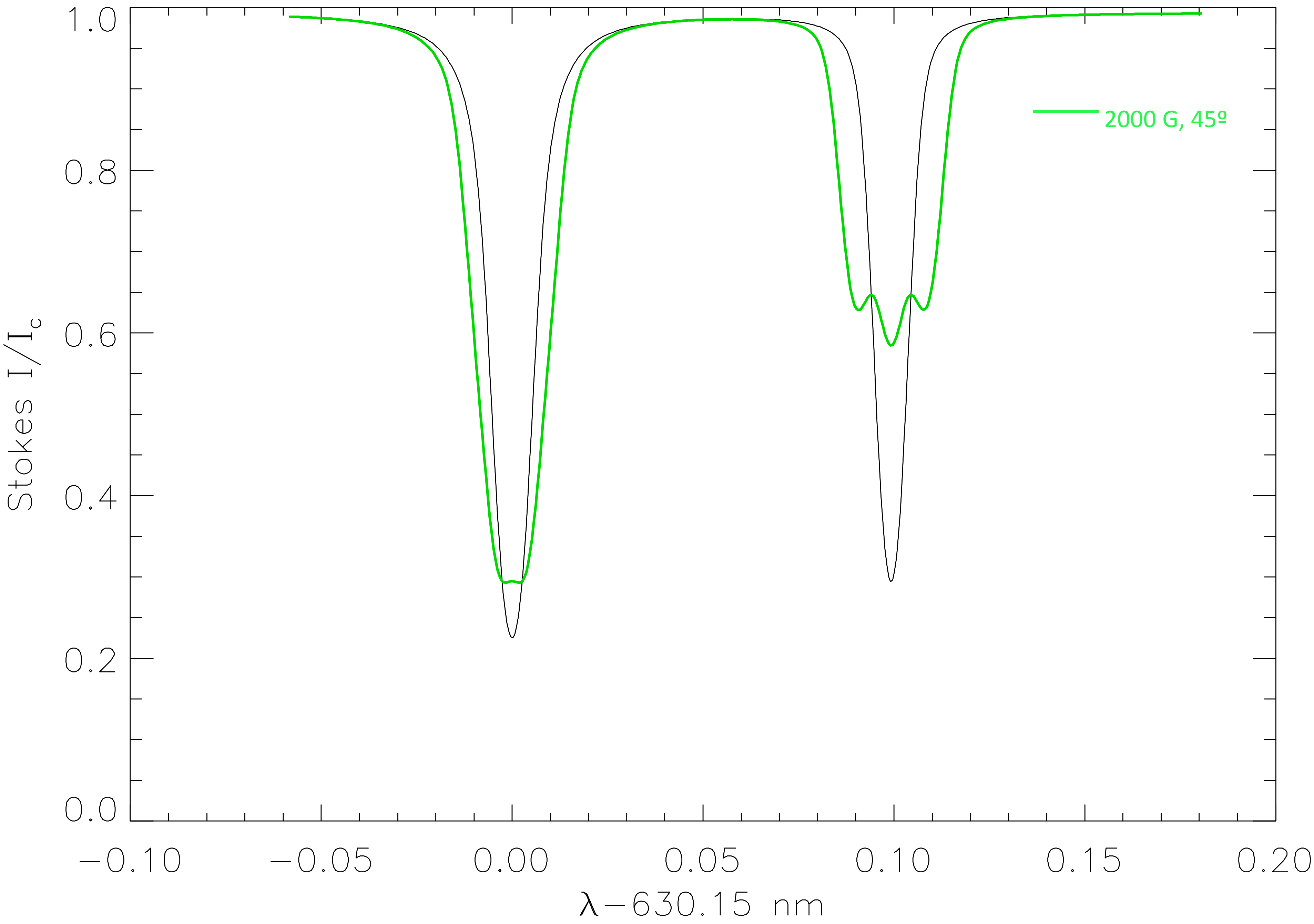
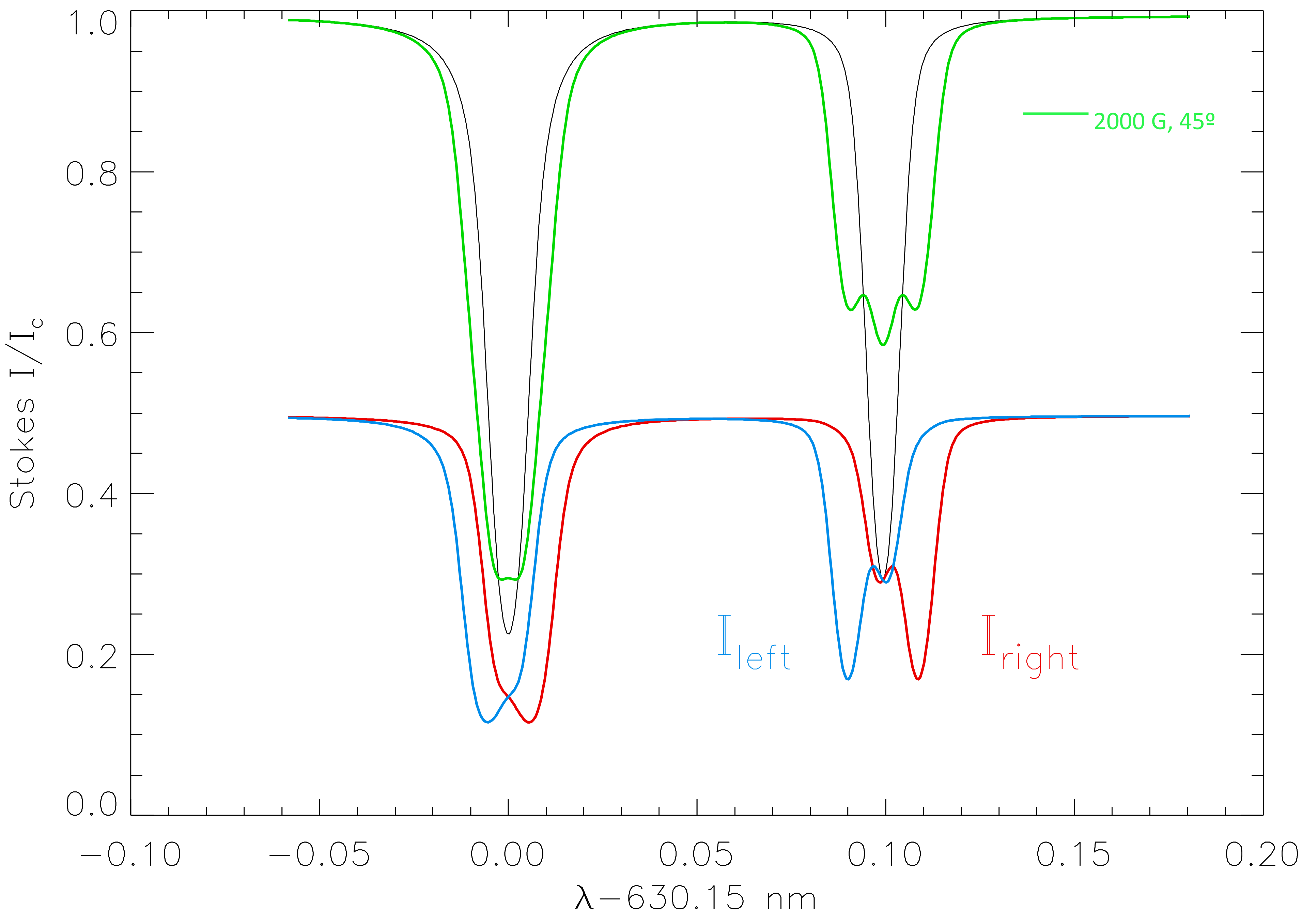
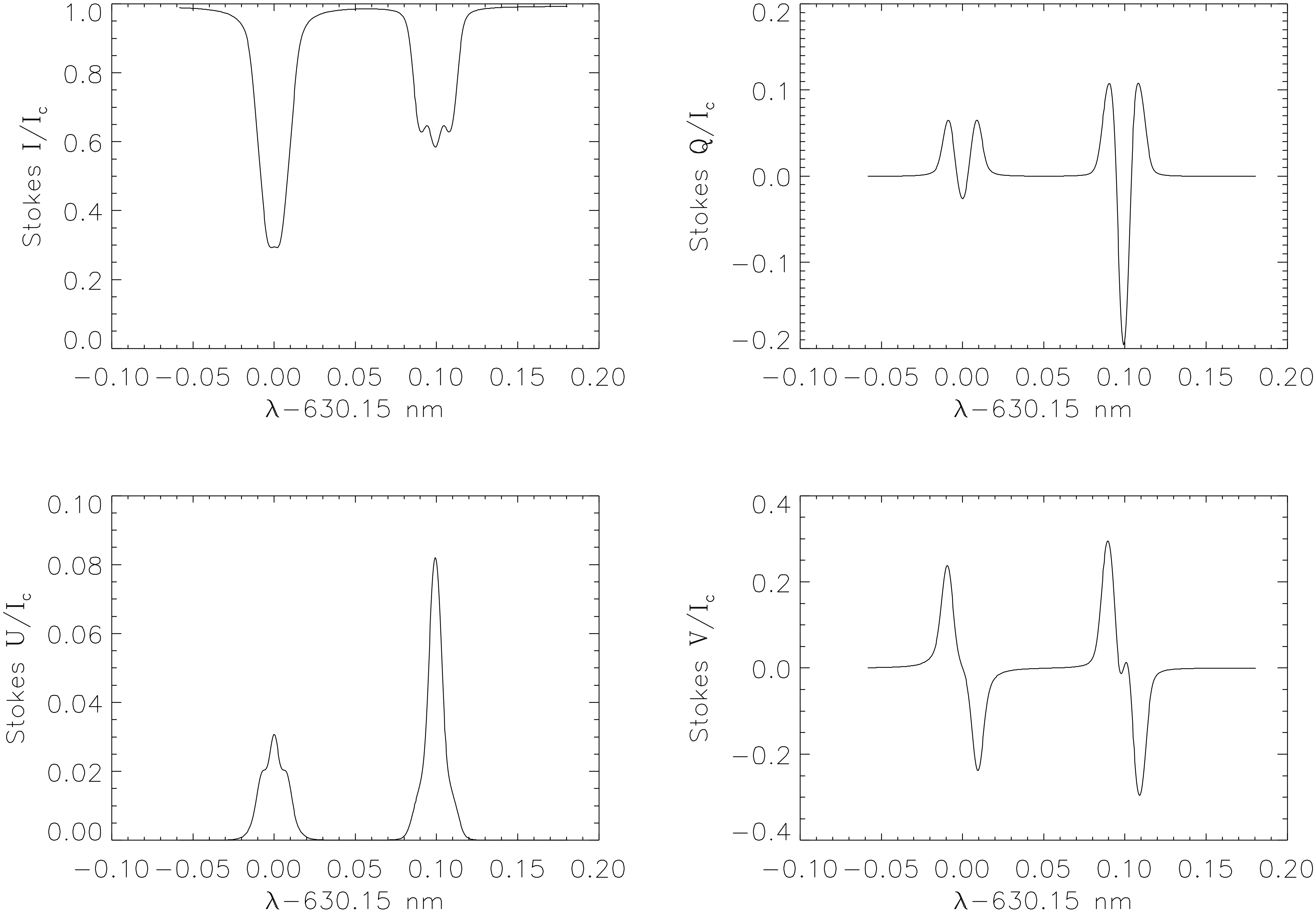


1: The RTE: formal solution & approximations



1: The RTE: formal solution & approximations



1: The RTE: formal solution & approximations

$$\frac{dI_\nu}{d\tau_c} = \kappa\left(I_\nu - S_\nu\right)$$

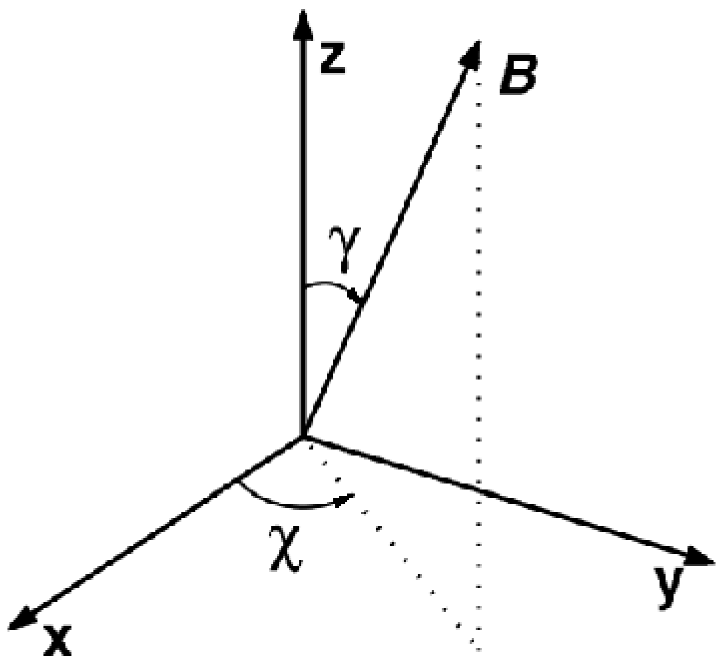
$$I_\nu \rightarrow \vec{I}_\nu = \begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix}$$

$$S_\nu \rightarrow \vec{S}_\nu = \begin{bmatrix} S_I \\ S_Q \\ S_U \\ S_V \end{bmatrix} \overset{LTE}{=} \begin{bmatrix} B_\nu \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

$$\kappa \rightarrow \overline{\overline{K}} = \frac{1}{k_c} \begin{bmatrix} \eta_I & \eta_Q & \eta_U & \eta_V \\ \eta_Q & \eta_I & \rho_V & -\rho_U \\ \eta_U & -\rho_V & \eta_I & \rho_Q \\ \eta_V & \rho_U & -\rho_Q & \eta_I \end{bmatrix}$$

Landi Degl’Innocenti & Landi Degl’Innocenti (1981)

1: The RTE: formal solution & approximations



$$\eta_I = k_c + \frac{1}{2} k_\ell \left[\eta_p \sin^2\gamma + \frac{\eta_b + \eta_r}{2} (1 + \cos^2\gamma) \right],$$

$$\eta_Q = \frac{1}{2} k_\ell \left(\eta_p - \frac{\eta_b + \eta_r}{2} \right) \sin^2\gamma \cos 2\chi,$$

$$\eta_U = \frac{1}{2} k_\ell \left(\eta_p - \frac{\eta_b + \eta_r}{2} \right) \sin^2\gamma \sin 2\chi,$$

$$\eta_V = \frac{1}{2} k_\ell (\eta_r - \eta_b) \cos\gamma,$$

$$\rho_Q = \frac{1}{2} k_\ell \left(\rho_p - \frac{\rho_b + \rho_r}{2} \right) \sin^2\gamma \cos 2\chi,$$

$$\rho_U = \frac{1}{2} k_\ell \left(\rho_p - \frac{\rho_b + \rho_r}{2} \right) \sin^2\gamma \sin 2\chi,$$

$$\rho_V = \frac{1}{2} k_\ell (\rho_r - \rho_b) \cos\gamma.$$

$$\kappa \to \overline{\overline{K}} = \frac{1}{k_c} \begin{bmatrix} \eta_I & \eta_Q & \eta_U & \eta_V \\ \eta_Q & \eta_I & \rho_V & -\rho_U \\ \eta_U & -\rho_V & \eta_I & \rho_Q \\ \eta_V & \rho_U & -\rho_Q & \eta_I \end{bmatrix}$$

Landi Degl'Innocenti & Landi Degl'Innocenti (1981)
Landi Degl'Innocenti & Landolfi (2004) Polarization in Spectral lines

1: The RTE: formal solution & approximations

$$\eta_\alpha = \frac{1}{\sqrt{\pi}\,\Delta\nu_{\rm D}} H(v - v_{\rm A} + \alpha\, v_B,\, a)$$

$$\rho_\alpha = \frac{1}{\sqrt{\pi}\,\Delta\nu_{\rm D}} L(v - v_{\rm A} + \alpha\, v_B,\, a)\ ,$$

$$H(v,a) = \frac{a}{\pi}\int_{-\infty}^{\infty} {\rm e}^{-y^2}\, \frac{1}{(v-y)^2 + a^2}\, {\rm d}y$$

$$L(v,a) = \frac{1}{\pi}\int_{-\infty}^{\infty} {\rm e}^{-y^2}\, \frac{v-y}{(v-y)^2 + a^2}\, {\rm d}y\ .$$

$$v = \frac{\lambda - \lambda_0}{\Delta\lambda_{\rm D}}\ , \qquad a = \frac{\lambda_0^2\, \Gamma}{c\,\Delta\lambda_{\rm D}}\ , \qquad v_{\rm A} = \frac{\lambda_0\, w_{\rm A}}{c\,\Delta\lambda_{\rm D}}$$

$$v_B = \frac{\lambda_0^2\, \nu_{\rm L}}{c\,\Delta\lambda_{\rm D}} = \frac{\lambda_0^2\, e_0\, B}{4\pi m c^2\,\Delta\lambda_{\rm D}} = \frac{\Delta\lambda_B}{\Delta\lambda_{\rm D}}\ ,$$

$$\Delta\lambda_{\rm D} = \frac{\lambda_0^2}{c}\,\Delta\nu_{\rm D} = \lambda_0\,\frac{w_{\rm T}}{c}\ ,$$

$$\eta_I = k_c + \frac{1}{2} k_\ell \left[\eta_p \sin^2\gamma + \frac{\eta_b + \eta_r}{2}(1 + \cos^2\gamma)\right],$$

$$\eta_Q = \frac{1}{2} k_\ell \left(\eta_p - \frac{\eta_b + \eta_r}{2}\right) \sin^2\gamma \cos 2\chi\ ,$$

$$\eta_U = \frac{1}{2} k_\ell \left(\eta_p - \frac{\eta_b + \eta_r}{2}\right) \sin^2\gamma \sin 2\chi\ ,$$

$$\eta_V = \frac{1}{2} k_\ell (\eta_r - \eta_b) \cos\gamma\ ,$$

$$\rho_Q = \frac{1}{2} k_\ell \left(\rho_p - \frac{\rho_b + \rho_r}{2}\right) \sin^2\gamma \cos 2\chi\ ,$$

$$\rho_U = \frac{1}{2} k_\ell \left(\rho_p - \frac{\rho_b + \rho_r}{2}\right) \sin^2\gamma \sin 2\chi\ ,$$

$$\rho_V = \frac{1}{2} k_\ell (\rho_r - \rho_b) \cos\gamma\ .$$

Landi Degl'Innocenti & Landi Degl'Innocenti (1981)
Landi Degl'Innocenti & Landolfi (2004) Polarization in Spectral lines

1: The RTE: formal solution & approximations

$$\phi_\alpha = \frac{1}{\sqrt{\pi}\,\Delta\nu_{\mathrm{D}}} H(v - v_{\mathrm{A}} + \alpha\, v_B,\, a)$$

$$\psi_\alpha = \frac{1}{\sqrt{\pi}\,\Delta\nu_{\mathrm{D}}} L(v - v_{\mathrm{A}} + \alpha\, v_B,\, a)\,,$$

$$H(v,a) = \frac{a}{\pi} \int_{-\infty}^{\infty} \mathrm{e}^{-y^2} \frac{1}{(v-y)^2 + a^2}\,\mathrm{d}y$$

$$L(v,a) = \frac{1}{\pi} \int_{-\infty}^{\infty} \mathrm{e}^{-y^2} \frac{v-y}{(v-y)^2 + a^2}\,\mathrm{d}y\,.$$

$$\eta_I = k_c + \frac{1}{2} k_\ell \left[\eta_p \sin^2\gamma + \frac{\eta_b + \eta_r}{2} (1 + \cos^2\gamma) \right],$$

$$\left. \frac{\eta_r}{} \right) \sin^2\gamma \cos 2\chi\,,$$

$$\left. \frac{\eta_r}{} \right) \sin^2\gamma \sin 2\chi\,,$$

$$\mathrm{s}\ \gamma\,,$$

$$\left. \frac{\rho_r}{} \right) \sin^2\gamma \cos 2\chi\,,$$

$$\left. \frac{\rho_r}{} \right) \sin^2\gamma \sin 2\chi\,,$$

$$\mathrm{s}\ \gamma\,.$$

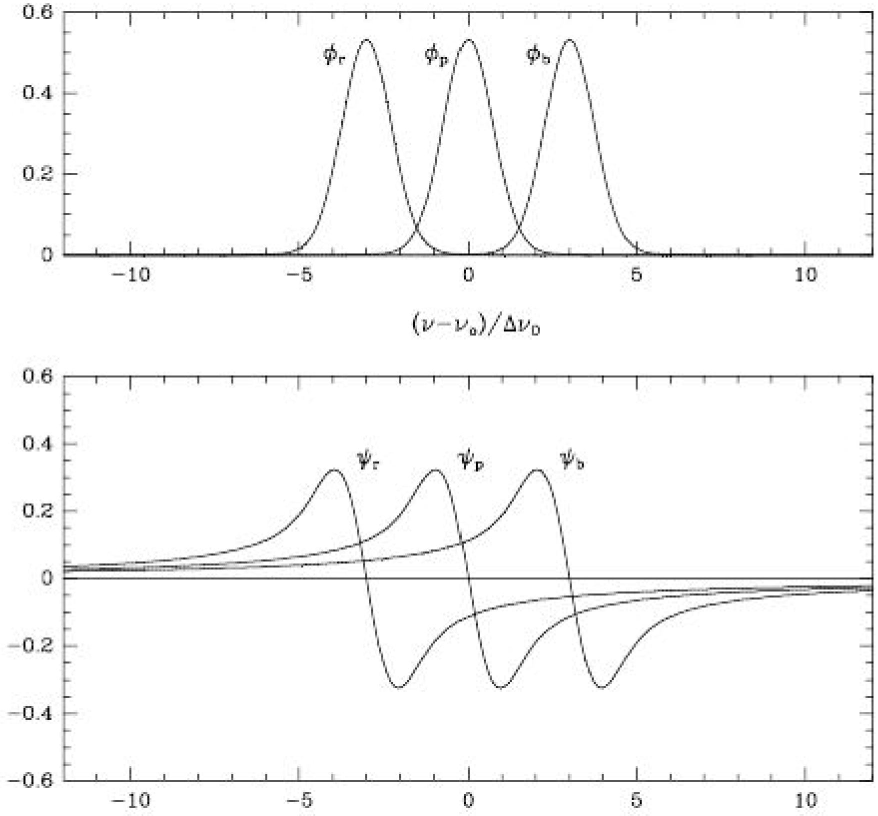


Fig.5.3. Absorption profiles ϕ and dispersion profiles ψ in units of $\Delta\nu_{\mathrm{D}}^{-1}$, corresponding to $v_B = 3$, $v_{\mathrm{A}} = 0$, and $a = 0.05$. Note that the magnetic field is 12 times stronger than in Fig.5.2.

$$v = \frac{\lambda - \lambda_0}{\Delta\lambda_{\mathrm{D}}}\,, \qquad a = \frac{\lambda_0^2\, \Gamma}{c\, \Delta\lambda_{\mathrm{D}}}$$

$$v_B = \frac{\lambda_0^2\, \nu_{\mathrm{L}}}{c\, \Delta\lambda_{\mathrm{D}}} = \frac{\lambda_0^2\, e_0\, B}{4\pi m c^2\, \Delta\lambda_{\mathrm{D}}} - \ \ \Delta\lambda_{\mathrm{D}}\,,$$

Landi Degl'Innocenti & Landi Degl'Innocenti (1981)

$$\Delta\lambda_{\mathrm{D}} = \frac{\lambda_0^2}{c}\, \Delta\nu_{\mathrm{D}} = \lambda_0 \frac{w_{\mathrm{T}}}{c}\,,$$

$$w_{\mathrm{T}} = \sqrt{\frac{2 k_{\mathrm{B}} T}{\mu M} + \xi^2}\,,$$

1: The RTE: formal solution & approximations

$$\frac{d\vec{I}_\nu}{d\tau_c} = \overline{\overline{K}}\left(\vec{I}_\nu - \vec{S}_\nu\right)$$

$$\frac{dI_\nu}{d\tau_c} = \kappa\left(I_\nu - S_\nu\right)$$

$$\frac{d\overline{\overline{O}}}{d\tau_c} \equiv -\overline{\overline{O}}\,\overline{\overline{K}}$$

$$\frac{dO}{d\tau_c} \equiv -O\kappa$$

$$\overline{\overline{O}}(\tau) \approx e^{-\int_0^\tau \overline{\overline{K}}d\tau}$$

$$O(\tau) = e^{-\int_0^\tau \kappa d\tau}$$

$$\vec{I}_\nu = \overline{\overline{O}}(\tau_0)\vec{I}_\nu(\tau_0) + \int_0^{\tau_0} \overline{\overline{O}}(\tau_c)\overline{\overline{K}}\vec{S}_\nu d\tau_c$$

$$I_\nu = O(\tau_0)I_\nu(\tau_0) + \int_0^{\tau_0} O(\tau_c)\kappa S_\nu d\tau_c$$

2: The Response Functions

$$\frac{d\vec{I}_\nu}{d\tau_c} = \overline{\overline{K}}\left(\vec{I}_\nu - \vec{S}_\nu\right)$$

- Landi Degl'Innocenti & Landi Degl'Innocenti (1977) A&A 56, 111
- Ruiz Cobo & del Toro Iniesta (1994) A&A 283,129

$\overline{\overline{K}}$ & $\vec{S}_\nu$ depend on atmosphere $\vec{a} = (T(\tau), P(\tau), \vec{B}(\tau), v_{LoS}(\tau))$

Can we evaluate, in first order, how much change $\vec{I}_\nu$ when we perturb $x = a_i(\tau_j)$?

$$\frac{d(\vec{I}_\nu + \delta\vec{I}_\nu)}{d\tau_c} = \overline{\overline{(K + \delta K)}}\left[(\vec{I}_\nu + \delta\vec{I}_\nu) - (\vec{S}_\nu + \delta\vec{S}_\nu)\right]$$

$$\overline{\overline{\delta K}} \approx \frac{\partial \overline{\overline{K}}}{\partial x}\delta x \qquad \delta\vec{S} \approx \frac{\partial \vec{S}}{\partial x}\delta x$$

$$\frac{d(\delta\vec{I}_\nu)}{d\tau_c} = \overline{\overline{K}}\left[\delta\vec{I}_\nu - \tilde{\vec{S}}_\nu\right]$$

$$\tilde{\vec{S}}_\nu = \overline{\overline{K}}^{-1}\left[\overline{\overline{\delta K}}(\vec{I}_\nu - \vec{S}_\nu) - \delta\vec{S}_\nu\right]$$

$$\delta\vec{I}_\nu = \int_0^{\tau_c} \overline{\overline{O}}(\tau_c)\overline{\overline{K}}\tilde{\vec{S}}\, d\tau_c$$

$$\overline{\overline{O}}\,\overline{\overline{K}}\tilde{\vec{S}} = \boxed{\overline{\overline{O}}\left[\frac{\partial \overline{\overline{K}}}{\partial x}\left(\vec{I}_\nu - \vec{S}_\nu\right) - \overline{\overline{K}}\frac{\partial \vec{S}}{\partial x}\right]}\delta x$$

2: The Response Functions

$$\frac{d\vec{I}_\nu}{d\tau_c} = \overline{\overline{K}}\left(\vec{I}_\nu - \vec{S}_\nu\right)$$

- Landi Degl'Innocenti & Landi Degl'Innocenti (1977) A&A 56, 111
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Can we evaluate, in first order, how much change $\vec{I}_\nu$ when we perturb $x = a_i(\tau_j)$?

$$\frac{d(\vec{I}_\nu + \delta\vec{I}_\nu)}{d\tau_c} = \overline{\overline{(K + \delta K)}}\left[(\vec{I}_\nu + \delta\vec{I}_\nu) - (\vec{S}_\nu + \delta\vec{S}_\nu)\right]$$

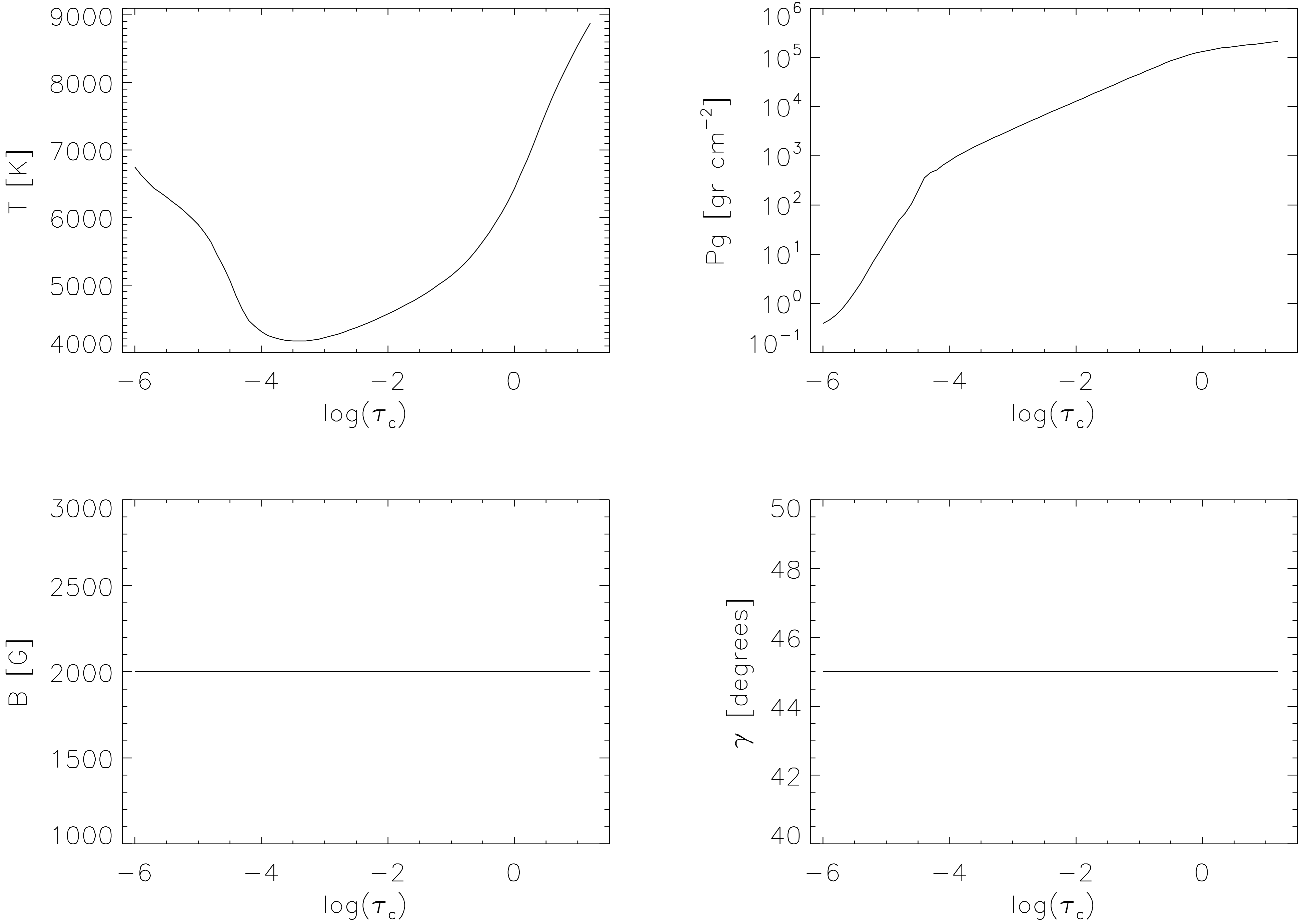
$$\frac{d(\delta\vec{I}_\nu)}{d\tau_c} = \overline{\overline{K}}\left[\delta\vec{I}_\nu - \tilde{\vec{S}}_\nu\right]$$

$$\overline{\overline{O}}\,\overline{\overline{K}}\,\tilde{\vec{S}} = \boxed{\overline{\overline{O}}\left[\frac{\partial\overline{\overline{K}}}{\partial x}\left(\vec{I}_\nu - \vec{S}_\nu\right) - \overline{\overline{K}}\frac{\partial\vec{S}}{\partial x}\right]}\delta x$$

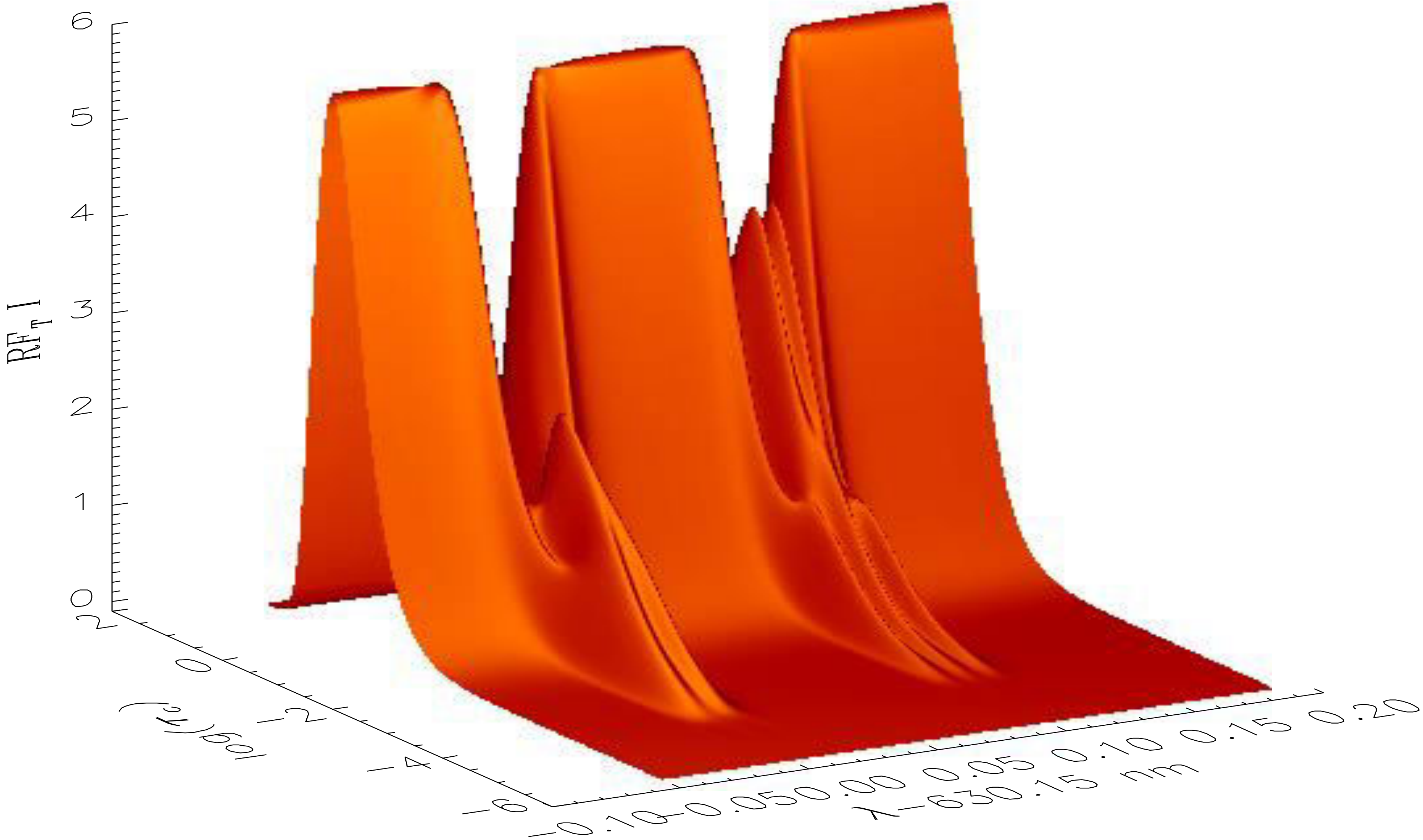
$$\delta\vec{I}_\nu = \int_0^{\tau_c} \overline{\overline{O}}(\tau_c)\,\overline{\overline{K}}\,\tilde{\vec{S}}\,d\tau_c \equiv \int_0^{\tau_c} R_x\,\delta x\,d\tau_c$$

$$\boxed{R_x \equiv \overline{\overline{O}}\left[\frac{\partial\overline{\overline{K}}}{\partial x}(\vec{I}_\nu - \vec{S}_\nu) - \overline{\overline{K}}\frac{\partial\vec{S}_\nu}{\partial x}\right]}$$

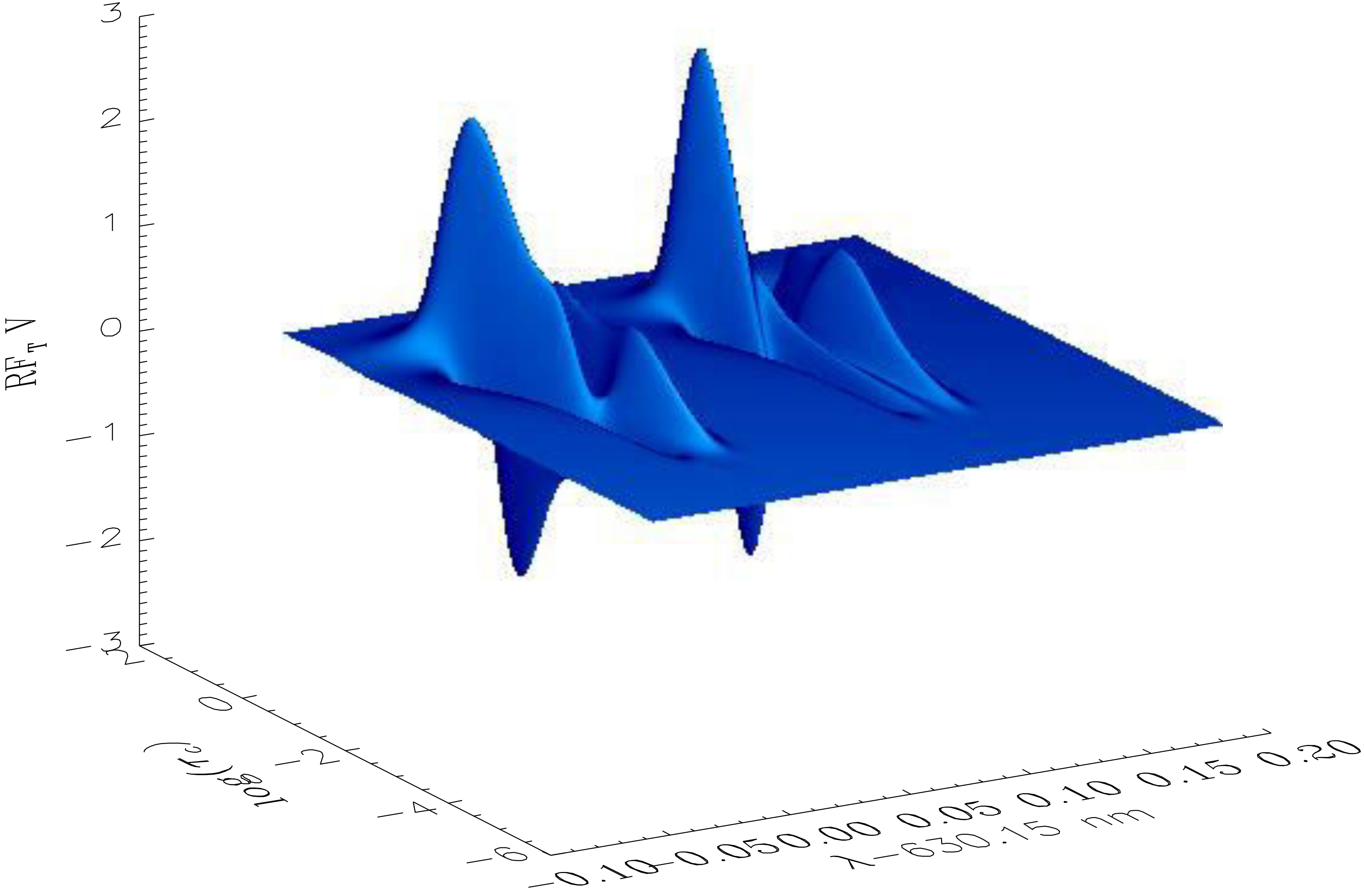
2: The Response Functions



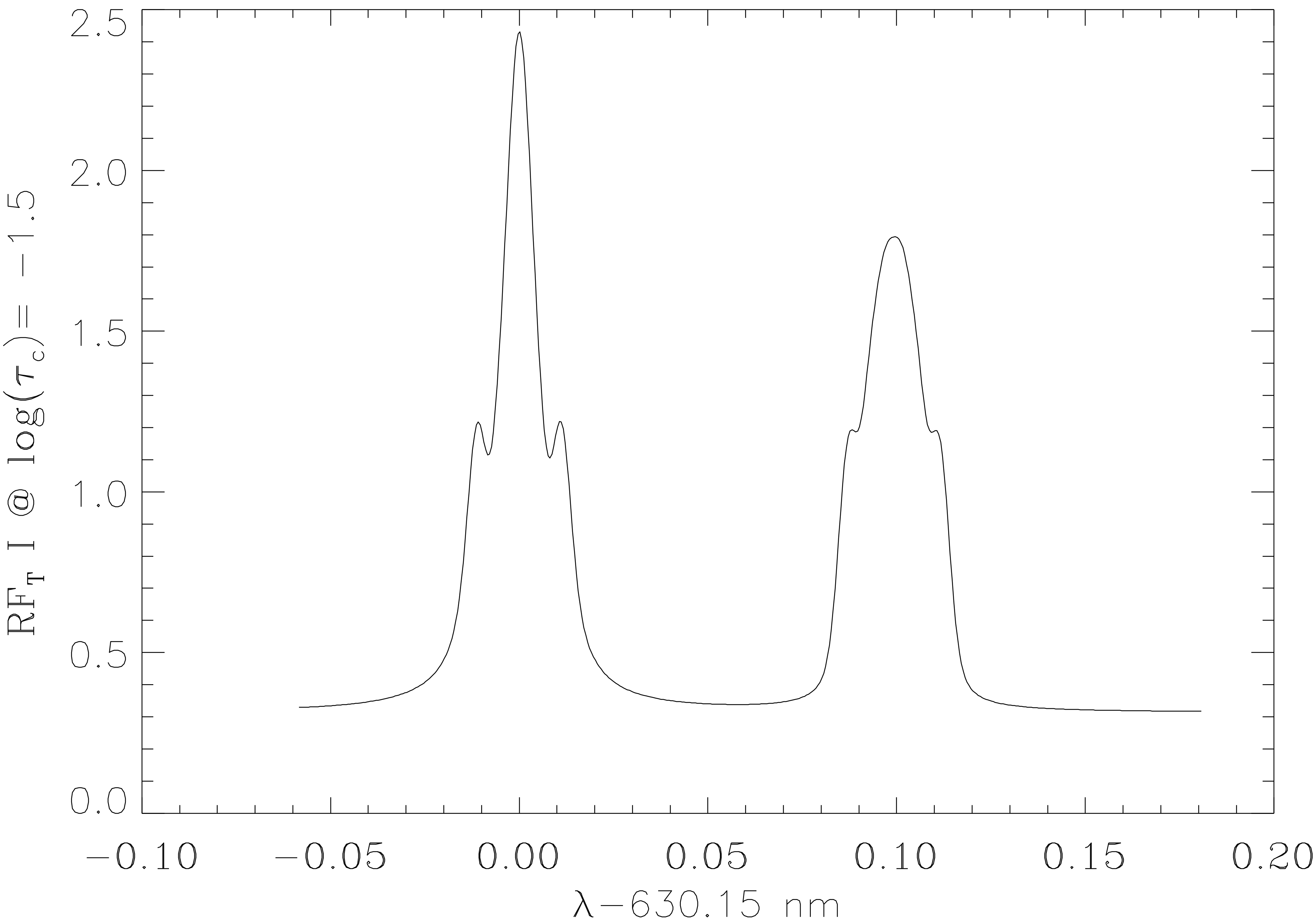
2: The Response Functions



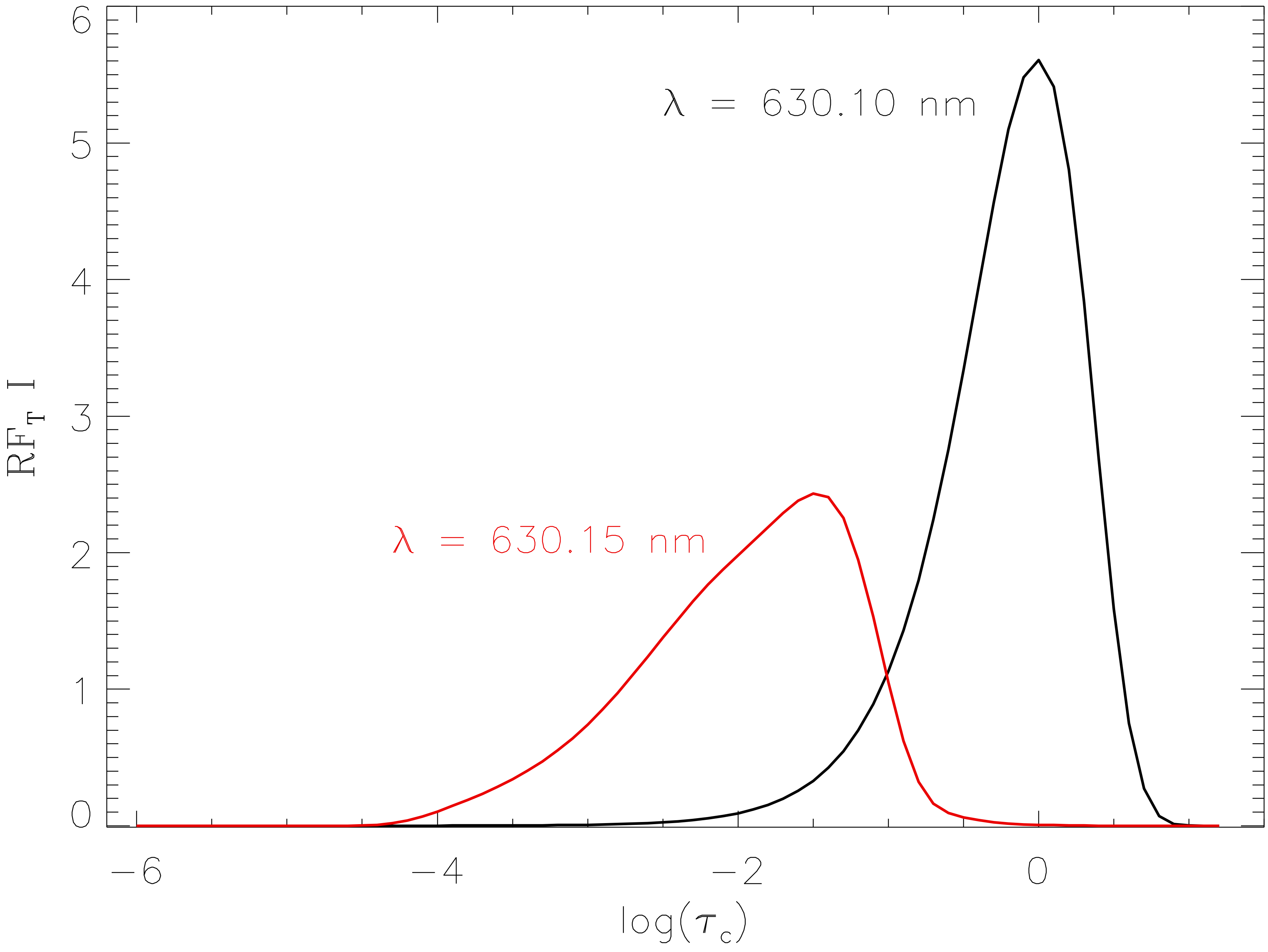
2: The Response Functions



2: The Response Functions



2: The Response Functions



2: The Response Functions

Table of physical magnitudes

$$\vec{a} = (T(\tau), P(\tau), \vec{B}(\tau), v_{LoS}(\tau))$$

+ atomic parameters

+ scenario

+ approximations

+ physical laws

Synthesis
(solving RTE)

$$\xrightarrow{} \vec{I}_{\nu} \ \& \ \vec{R}_{x}$$

$$\delta I_{\lambda_i} = \int R_{\lambda_i,x}\, \delta x \, \mathrm{d}\tau$$

$$\begin{pmatrix} \delta I_{\lambda_1} \\ \vdots \\ \delta I_{\lambda_n} \end{pmatrix} = \begin{pmatrix} R_{\lambda_1,x_1} & \cdots & R_{\lambda_1,x_m} \\ \cdot & \cdots & \cdot \\ R_{\lambda_n,x_1} & \cdots & R_{\lambda_n,x_m} \end{pmatrix} \begin{pmatrix} \delta x_1 \\ \vdots \\ \delta x_m \end{pmatrix}$$

3. What is an inversion technique? How does it work?

- Any method used to infer the physical conditions of the atmosphere from the interpretation of Stokes profile.
  (in a broad sense any "measurement in the Sun" is an inversión)

- We want: vector magnetic field, gas temperature, gas velocity, etc, at some layers in the Sun

- We need: assume some approximations. We will only be able to find some free parameters values such that we can reproduce the observations.

3. What is an inversion technique? How does it work?

-What's an IT?

Inhomogeneous Fredholm's ec. of the first kind:

$$g(t) = \int_a^b K(t,s) f(s) ds$$

$g(t)$ data

$K(t,s)$ kernel

$f(s)$ unknown

This equation, through a quadrature, becomes:

$$K \cdot f = g$$

as g is no null if we could evaluate K^{-1}

the solution: $f = K^{-1} \cdot g$ but… this is not the general case

3. What is an inversion technique? How does it work?

$$g(t) = \int_a^b K(t,s) f(s) ds$$

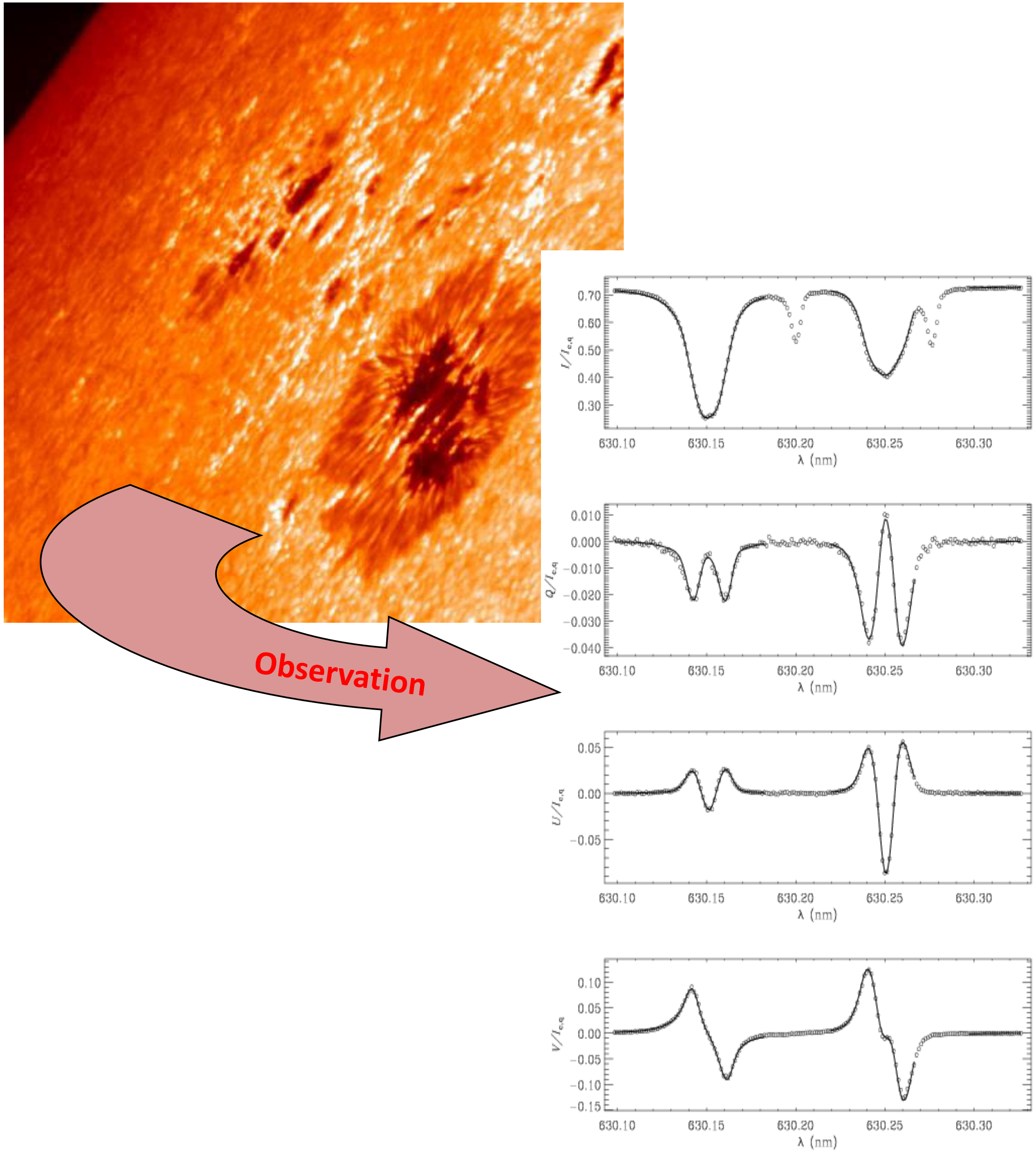
$f(s)$ become smoothed by the kernel $K(t,s)$

1) Small $g(t)$ perturbations are compatible with huge changes in $f(s)$

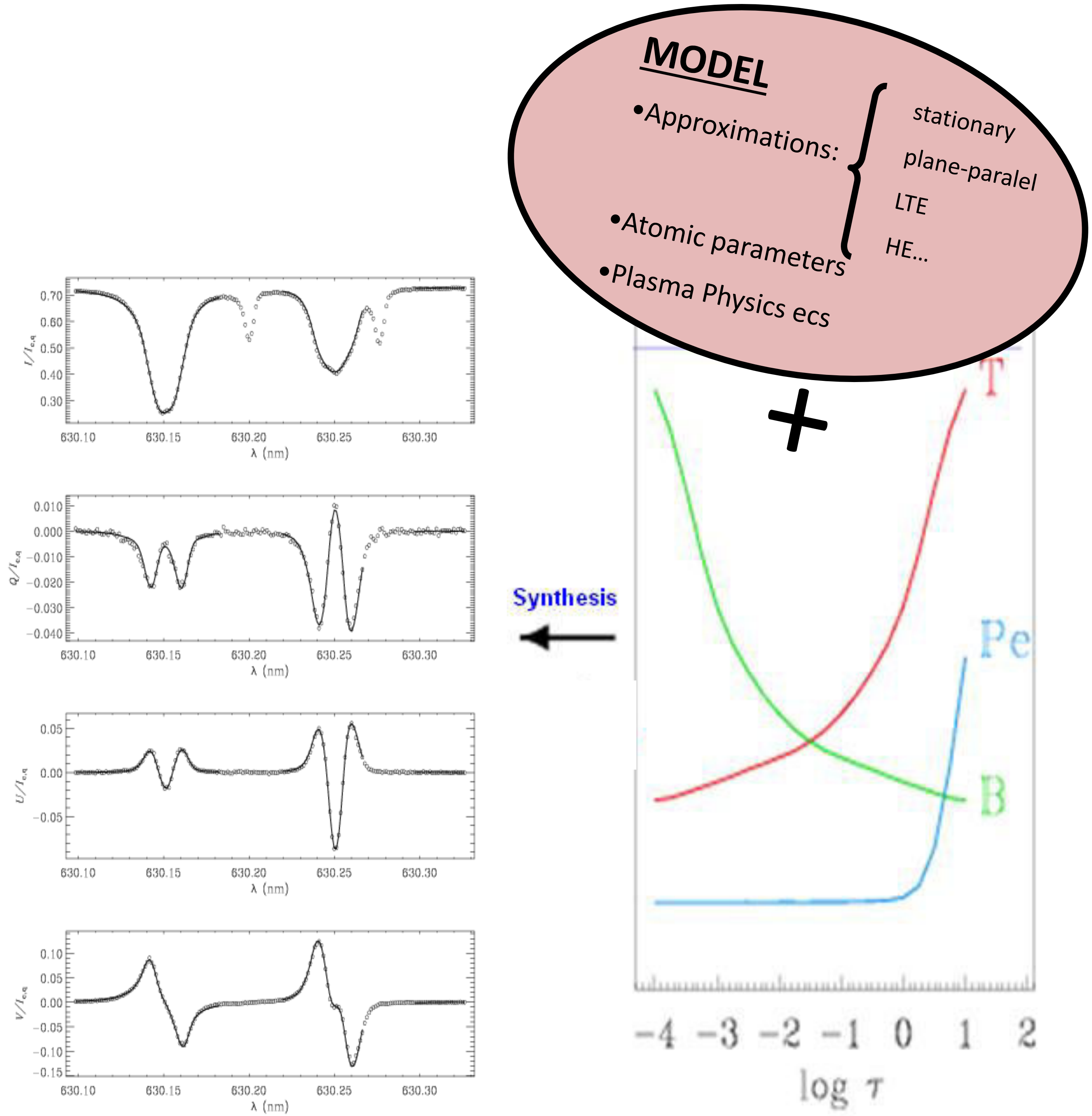
2) Smoothing means lost information, then “recover” $f(s)$ is imposible

3) We have a discrete set of $g(t)$ values and we’d wish a function $f(s)$

3. What is an inversion technique? How does it work?

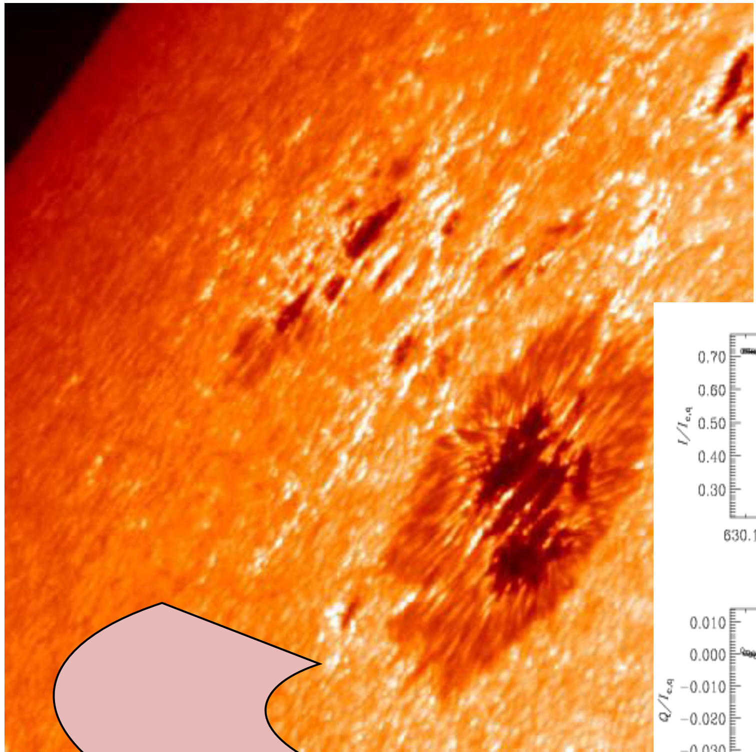


3. What is an inversion technique? How does it work?

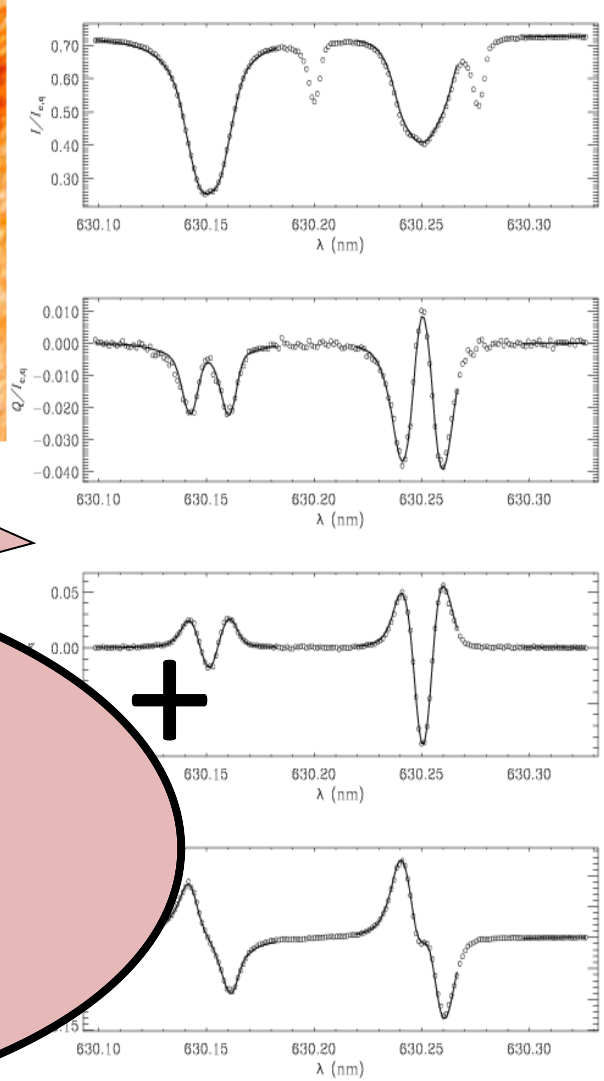


3. What is an inversion technique? How does it work?

- The model (except free parameters values) must be known a priori
- We only fit the free parameters

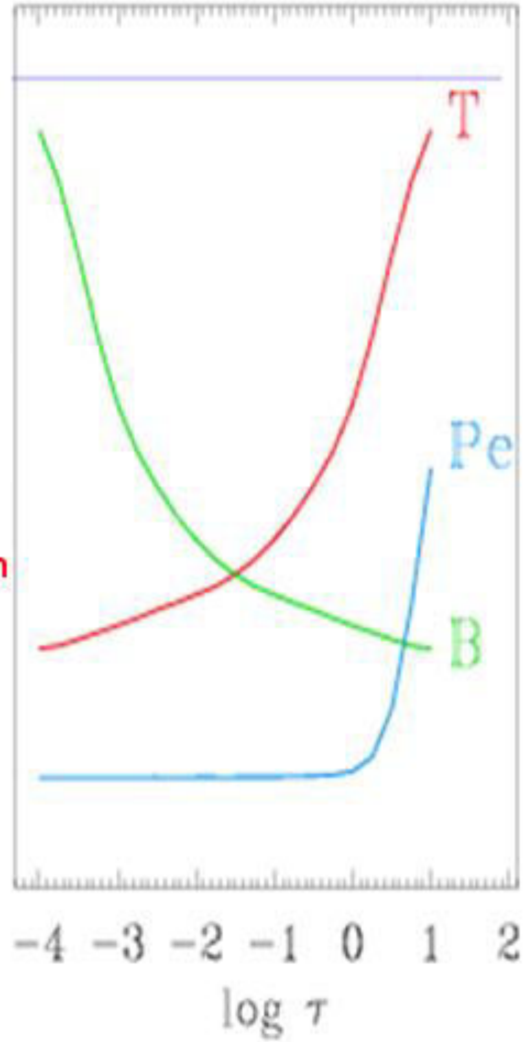


Observation



+

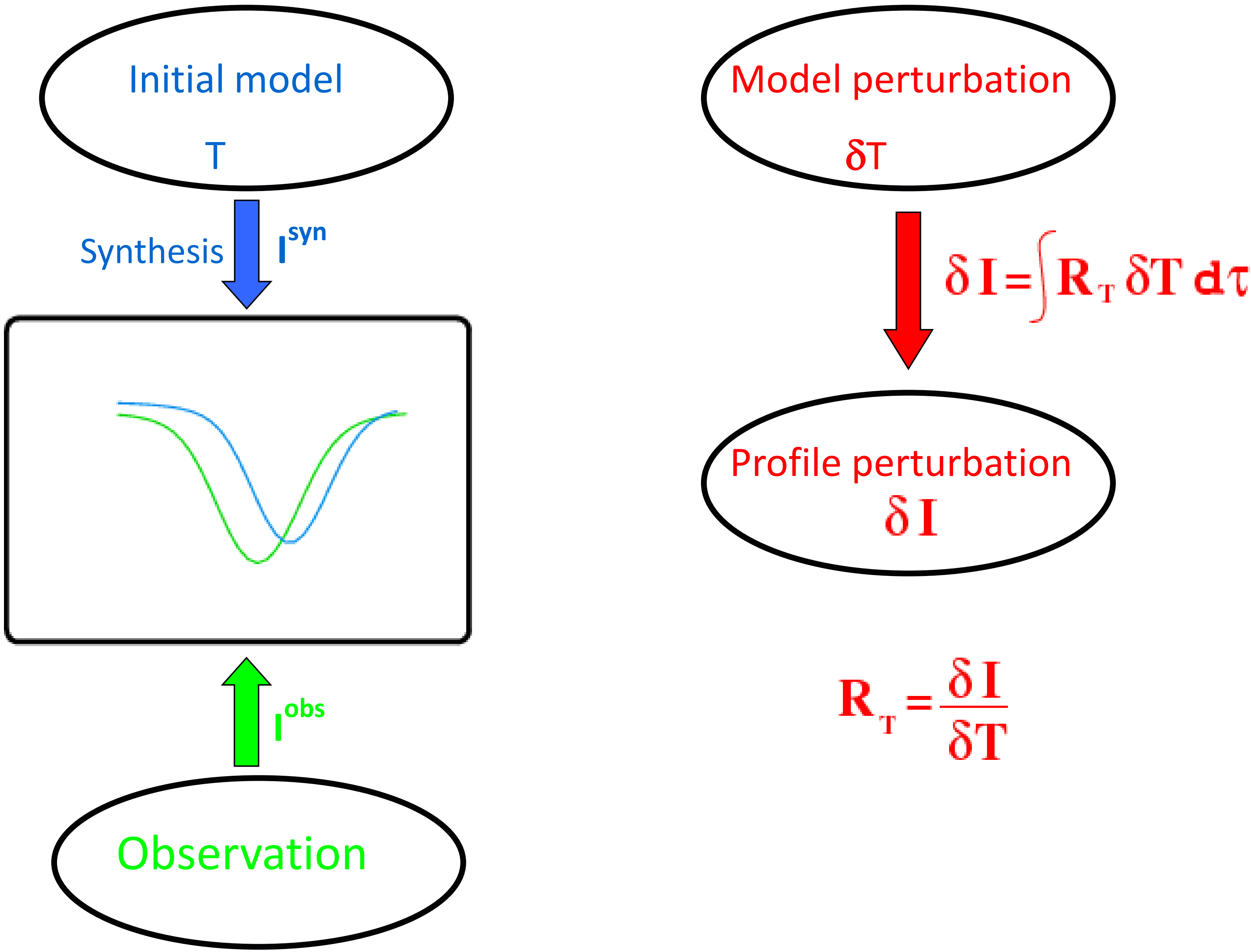
Inversion



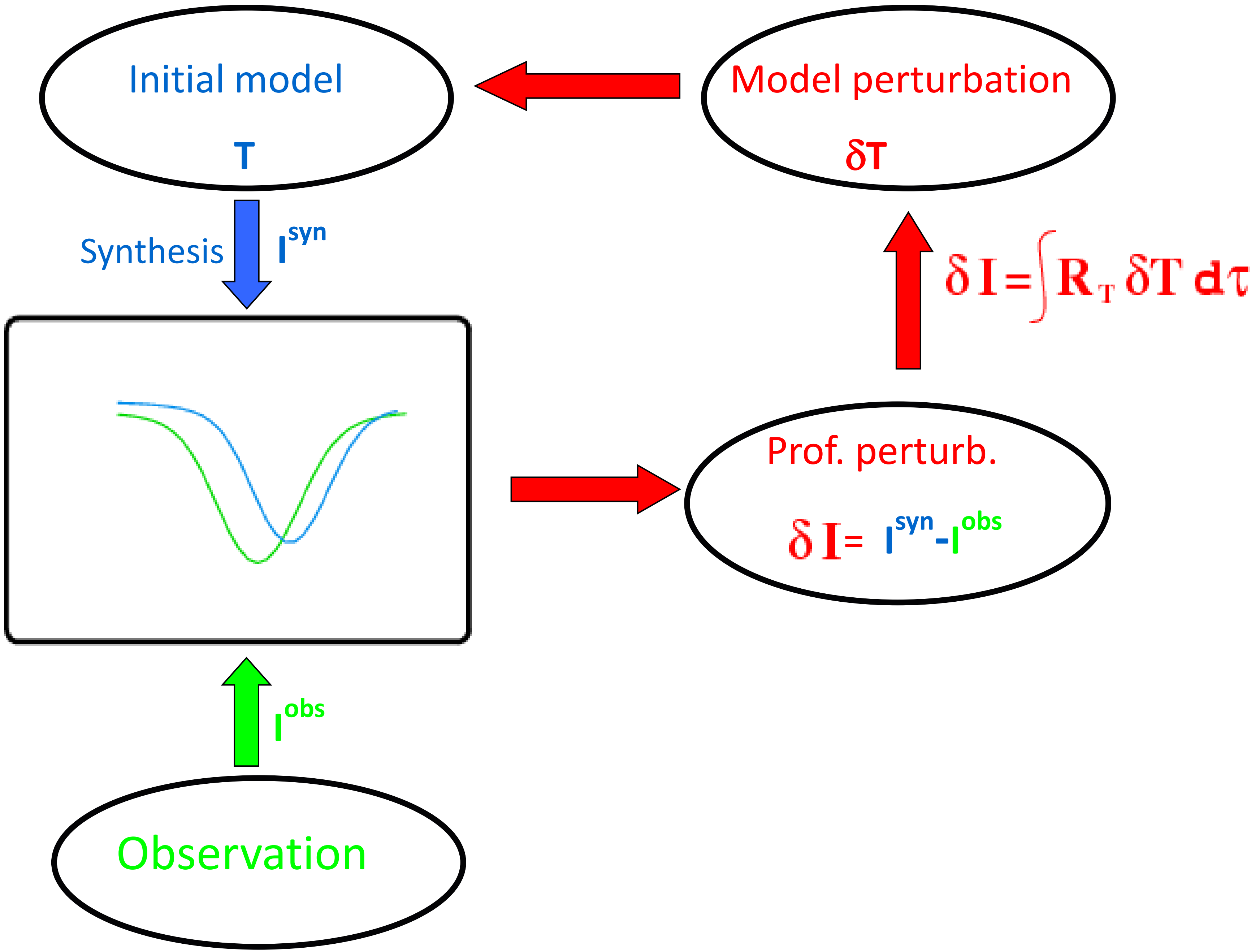
MODEL

- Approximations:
  - stationary
  - plane-paralel
  - LTE
  - HE…
- Atomic parameters
- Plasma Physics ecs

4: The SIR code



4: The SIR code



4: The SIR code

- Inversion driven by χ^2-minimization

$$\chi^2(\mathbf{a}) = \frac{1}{N_{\rm free}} \sum_{j=1}^{4} \sum_{i=1}^{N_\lambda} \frac{w_{ij}^2}{\sigma_j^2} \left[I_j^{\rm obs}(\lambda_i) - I_j^{\rm syn}(\lambda_i, \mathbf{a}) \right]^2$$

- Minimization: 2nd order Levenberg-Marquardt algorithm

$$\nabla \chi^2(\mathbf{a}) + \mathbf{A}(\chi^2) \cdot \delta \mathbf{a} = 0$$

4: The SIR code

$$\chi^2 \equiv \frac{1}{\nu} \sum_{i=1}^{M} \left[I^{\mathrm{obs}}(\lambda_i) - I^{\mathrm{sin}}(\lambda_i, \vec{a}) \right]^2$$

Least squares

$$\vec{a} = (T_1, T_2, ...T_n, B_1, B_2, ...B_n, ...)$$

$$\nabla \chi^2(\vec{a}) = - [A]\, \delta\vec{a}$$

$$\delta\vec{a} = [A]^{-1} \cdot \nabla \chi^2(\vec{a})$$

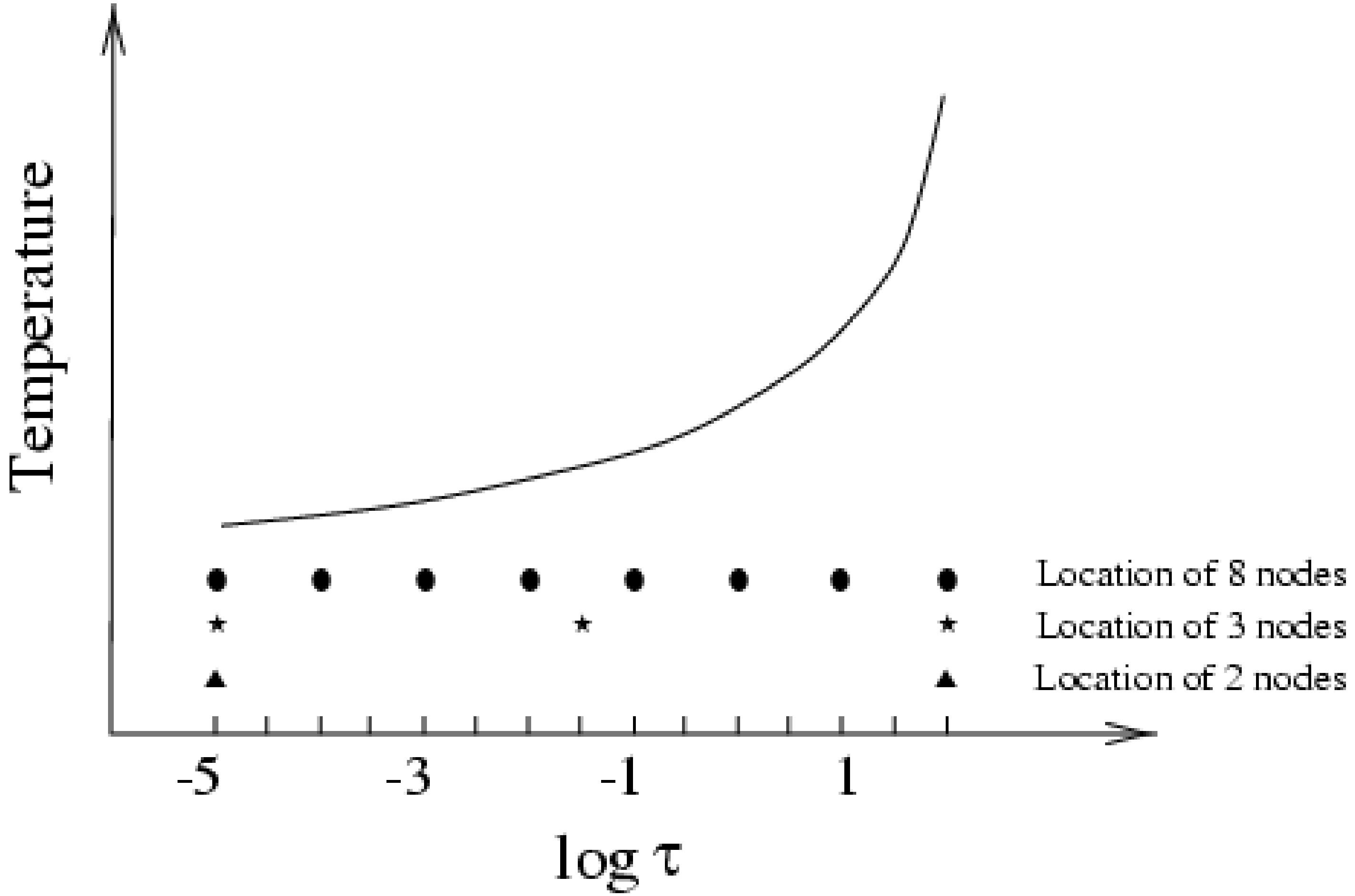
4: The SIR code

$$\delta\vec{a} = [A]^{-1} \cdot \nabla\chi^2(\vec{a})$$

inverting A

- Very large (1)
- Singular (2)

1) Sequential increase of unknown number



4: The SIR code

$$\delta\vec{a} = [A]^{-1} \cdot \nabla\chi^2(\vec{a})$$

inverting A

$\begin{cases} \bullet \text{ Very large (1)} \\ \bullet \text{ Singular (2)} \end{cases}$

1) Sequential increase of number of unknowns

2) Singularities elimination through SVD (Singular Value Decomposition)

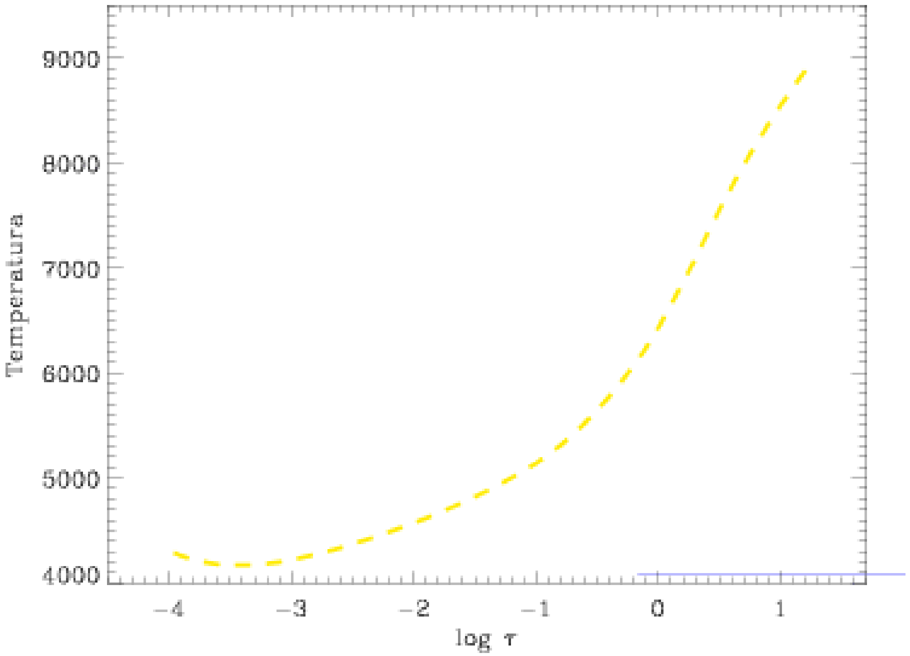
$A = U\, W\, V^T$ with U & V ortonormal matrix

y W =diagonal(w_{jj})

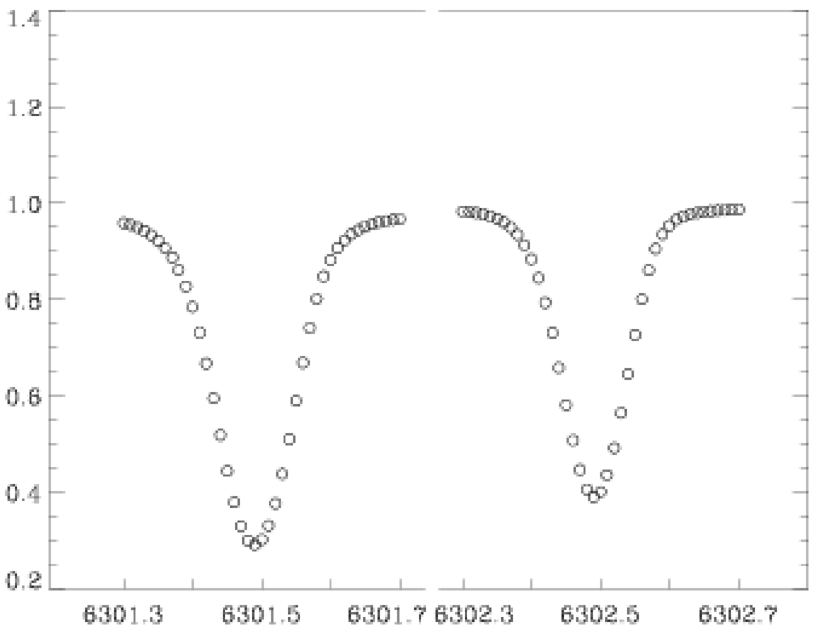
$A^{-1} = V\, W^{-1}\, U^T$ with W^{-1} =diagonal($1/w_{jj}$)

but doing $(W^{-1})_{jj}=0$ si $w_{jj} \cong 0$

4: The SIR code

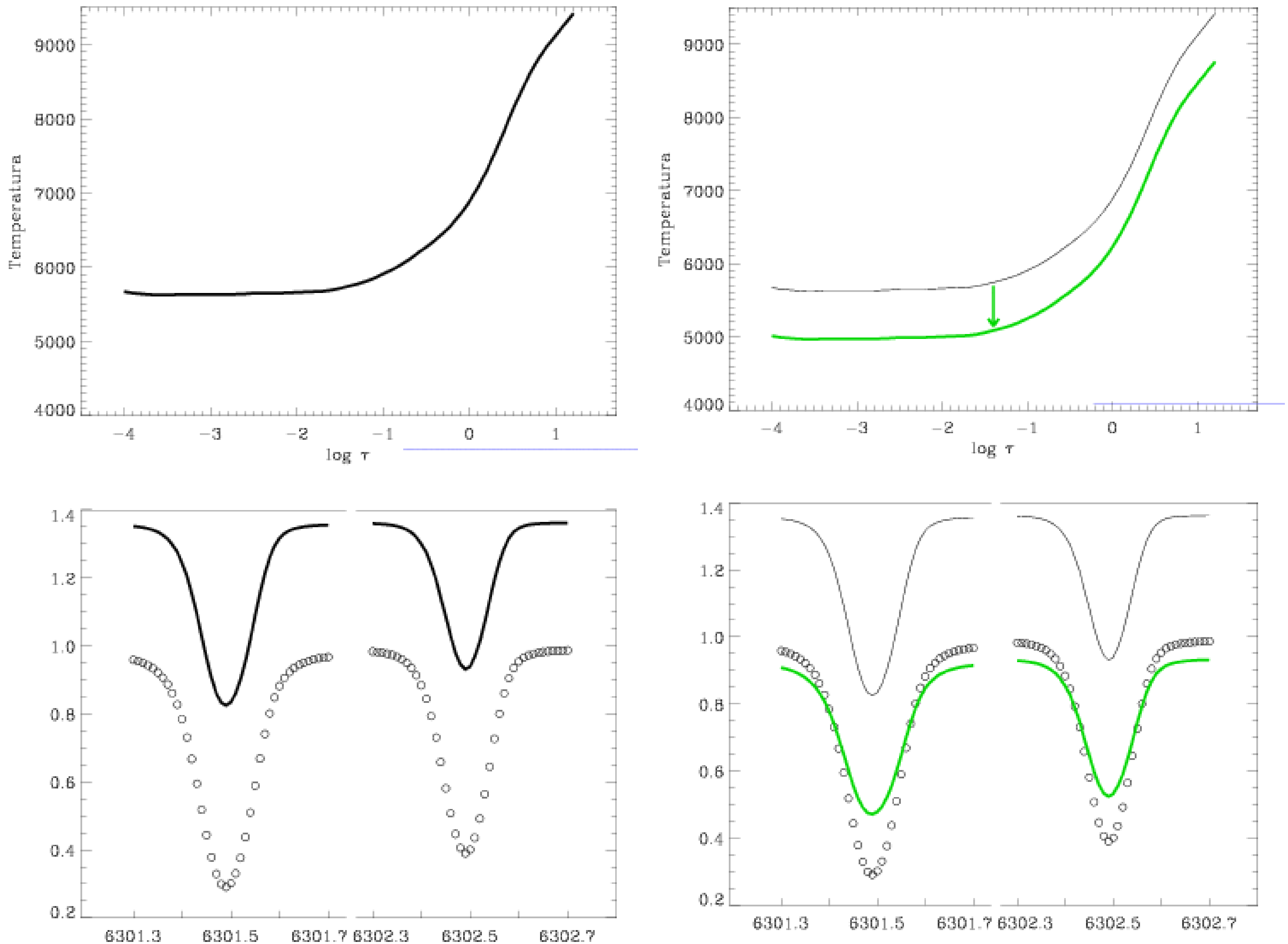


The “real” SUN

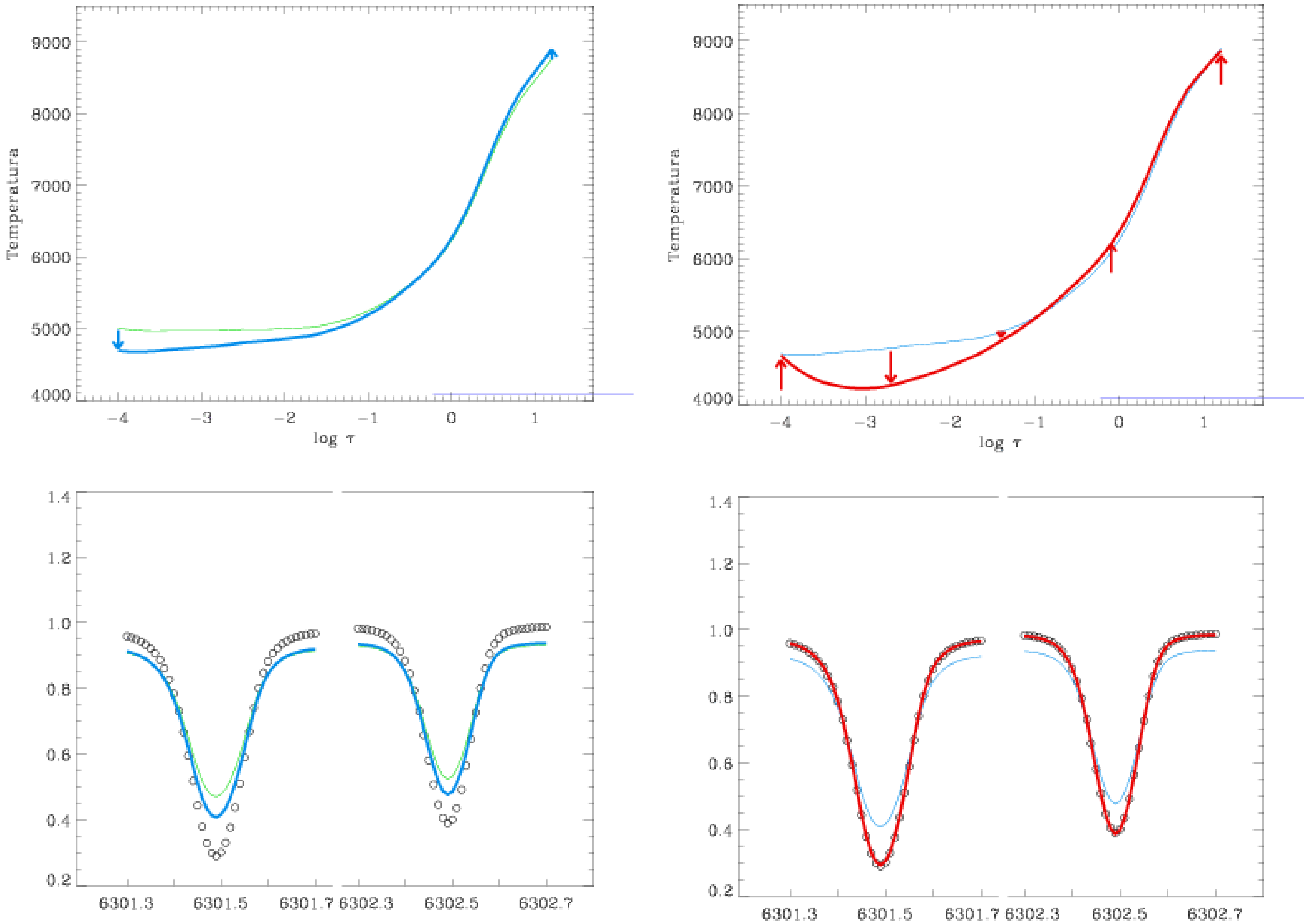


Synthetic “observations”

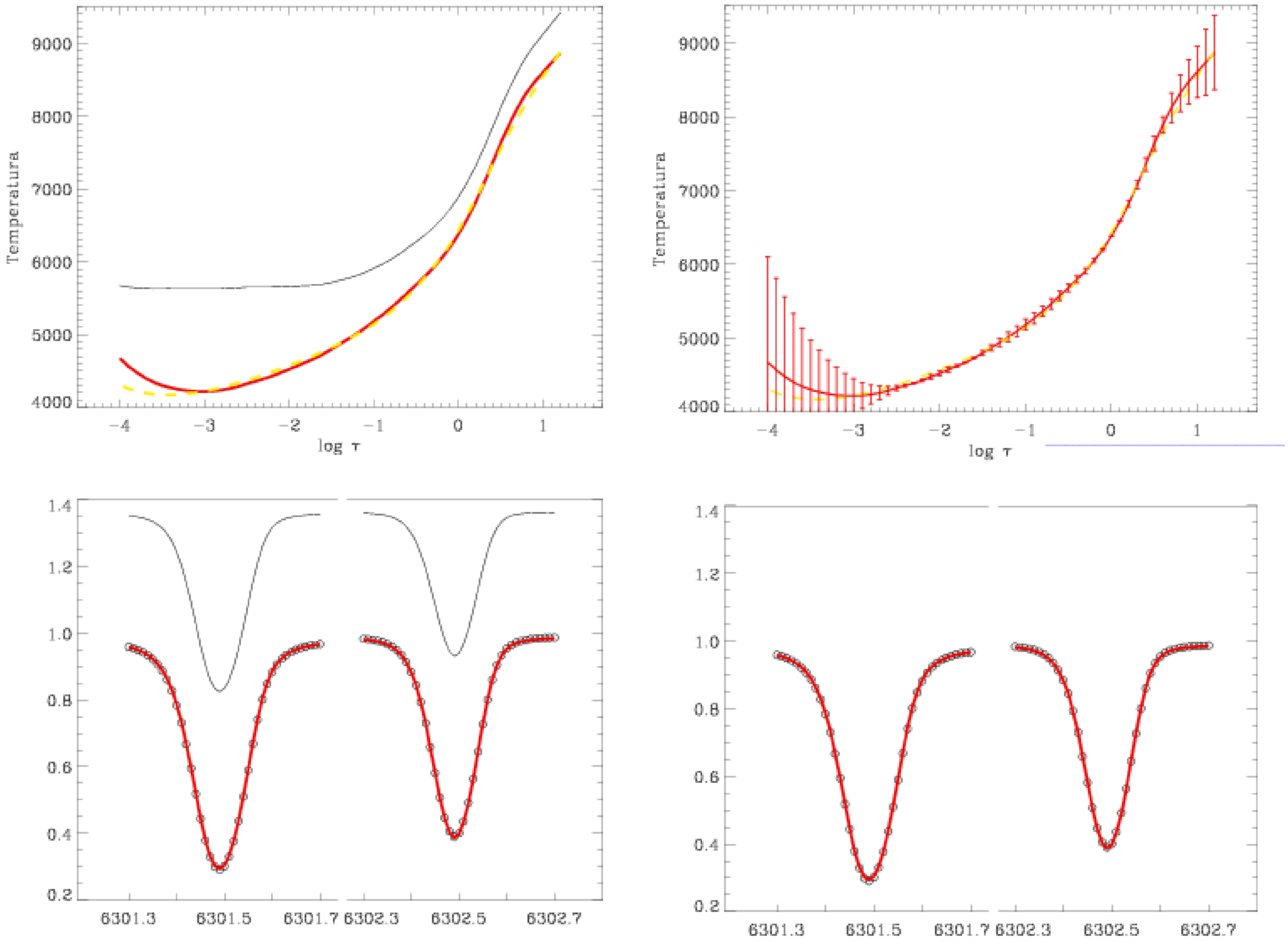
4: The SIR code



4: The SIR code



4: The SIR code



4: The SIR code

$$\delta x_{\tau_i} = \sum_j a_{ij} \delta x_{\tau_j}$$

at node j

$$\delta \vec{I}_\nu = \int_0^{\tau_c} R_x \delta x d\tau_c \approx \Delta\tau \sum_i R_{x_i} \delta x_{\tau_i} = \Delta\tau \sum_i R_{x_i} \left(\sum_j a_{ij} \delta x_{\tau_j} \right) =$$

$$= \Delta\tau \sum_j \left(\sum_i a_{ij} R_{x_i} \right) \delta x_{\tau_j} = \Delta\tau \sum_j \widehat{R}_j \delta x_{\tau_j}$$

$$\widehat{R}_j = \sum_i a_{ij} R_{x_i}$$

Equivalent Response Function at nodes

4: The SIR code

$$\chi^2(\vec{x}) = \sum_i c_i \left[I_i^{obs} - I_i^{syn}(\vec{x})\right]^2$$

$\vec{x}$ Parameters at nodes

$$\nabla\chi^2(\vec{x}) + \overline{\overline{A}} \cdot \delta\vec{x} = 0$$

$$\nabla\chi^2(\vec{x}) = \left[I_i^{obs} - I_i^{syn}(\vec{x})\right]\widehat{R}$$

$$\overline{\overline{A_{ij}}} \equiv \frac{\partial^2\chi^2}{\partial x_i \partial x_j} \approx \frac{\partial\chi^2}{\partial x_i}\frac{\partial\chi^2}{\partial x_j}$$

$$\delta\vec{x} = -\overline{\overline{A}}^{-1} \cdot \nabla\chi^2(\vec{x})$$

Levemberg-Marquardt

+

SVD

$$\overline{\overline{A_{ij}}} \equiv \frac{\partial^2\chi^2}{\partial x_i \partial x_j} \rightarrow \begin{pmatrix} \left(\frac{\partial\chi^2}{\partial x_1}\frac{\partial\chi^2}{\partial x_1}\right)(1+e^{\lambda}) & \frac{\partial\chi^2}{\partial x_1}\frac{\partial\chi^2}{\partial x_2} & \dots & \frac{\partial\chi^2}{\partial x_1}\frac{\partial\chi^2}{\partial x_n} \\ \dots & \left(\frac{\partial\chi^2}{\partial x_2}\frac{\partial\chi^2}{\partial x_2}\right)(1+e^{\lambda}) & \dots & \dots \\ \dots & \dots & \dots & \dots \\ \dots & \dots & \dots & \left(\frac{\partial\chi^2}{\partial x_n}\frac{\partial\chi^2}{\partial x_n}\right)(1+e^{\lambda}) \end{pmatrix}$$

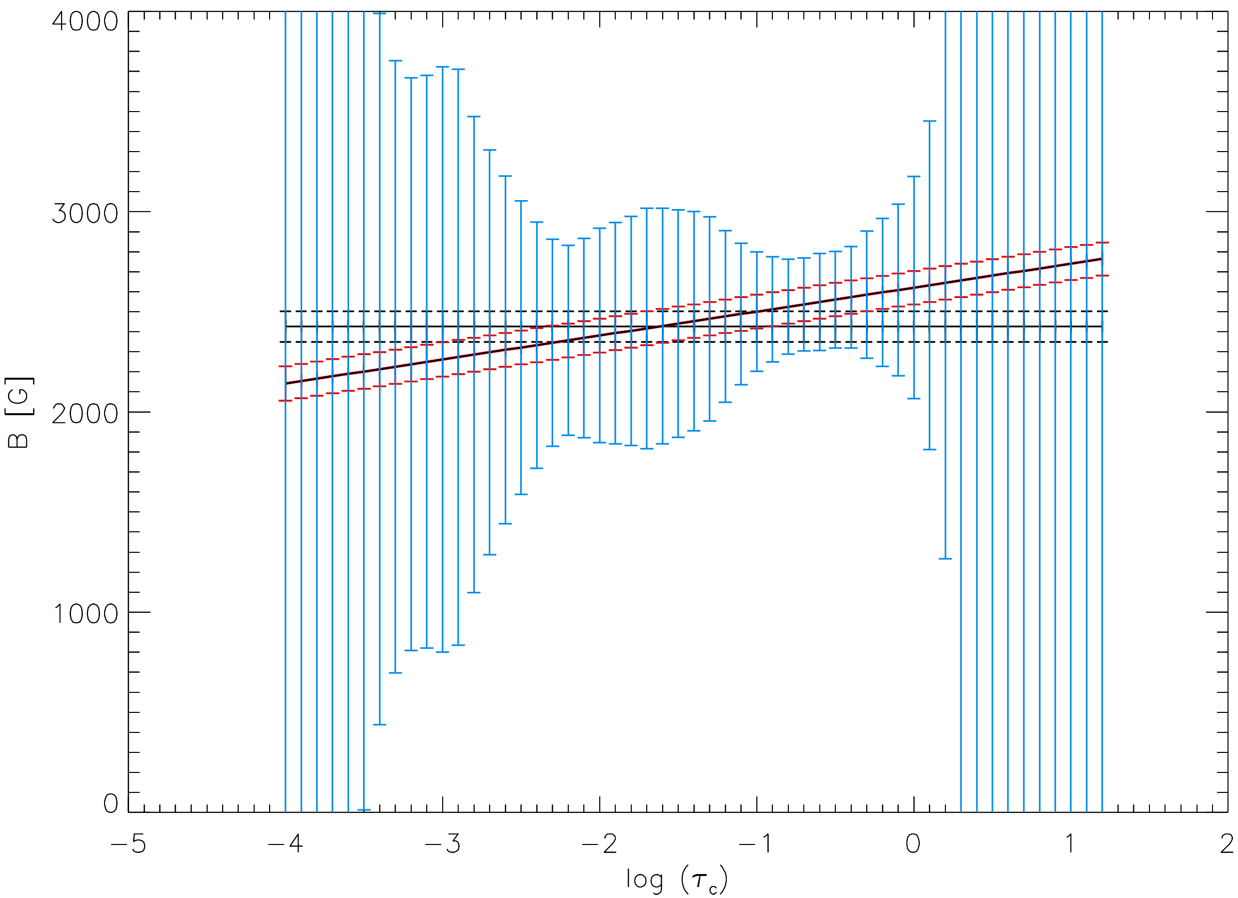
Numerical Recipes (2007) Press et al.

4: The SIR code

Error bars:

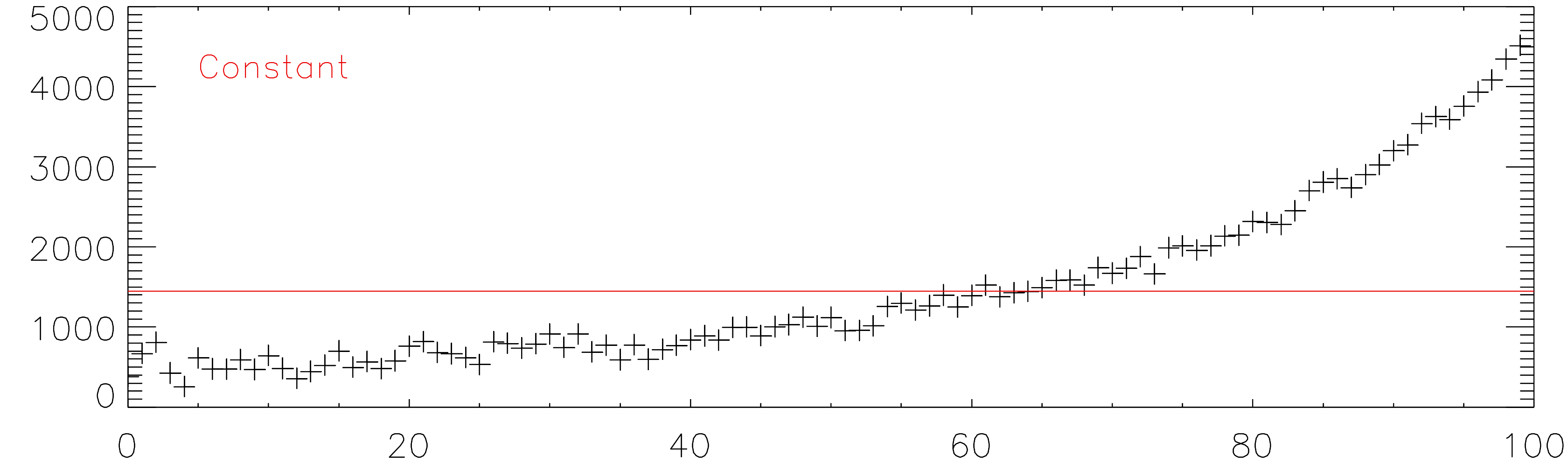
Uncertainties:

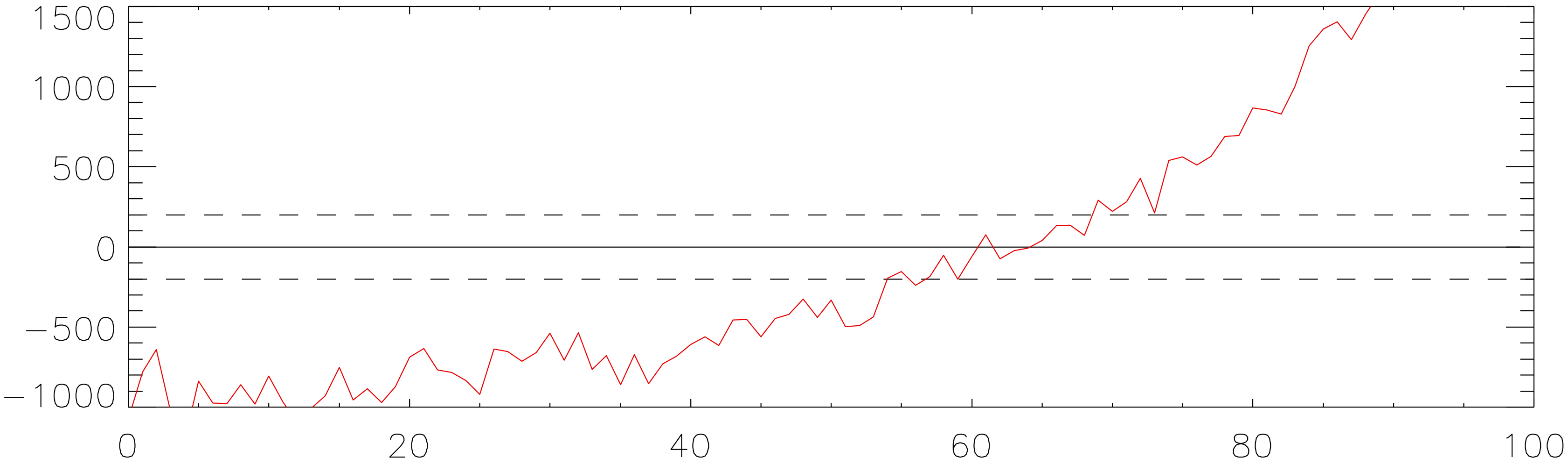
$$\sigma_x(\tau) = \frac{\sigma\left(I^{obs} - I^{syn}\right)}{\max_\lambda\left(\left|R_x(\lambda,\tau)\right|\right)}$$



4: The SIR code

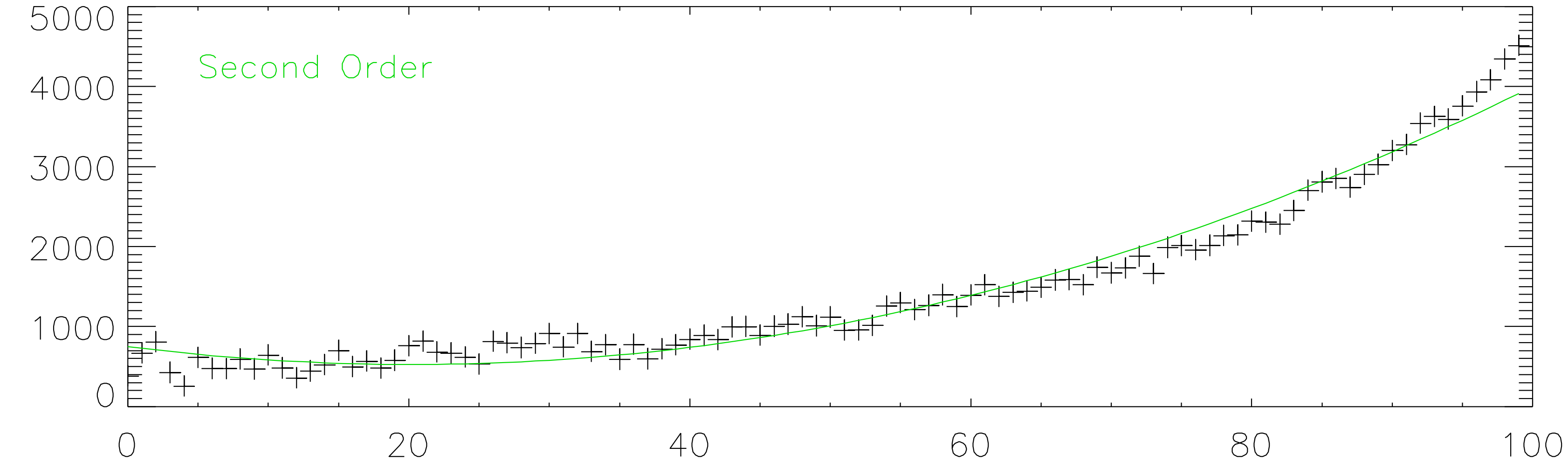
Unicity?

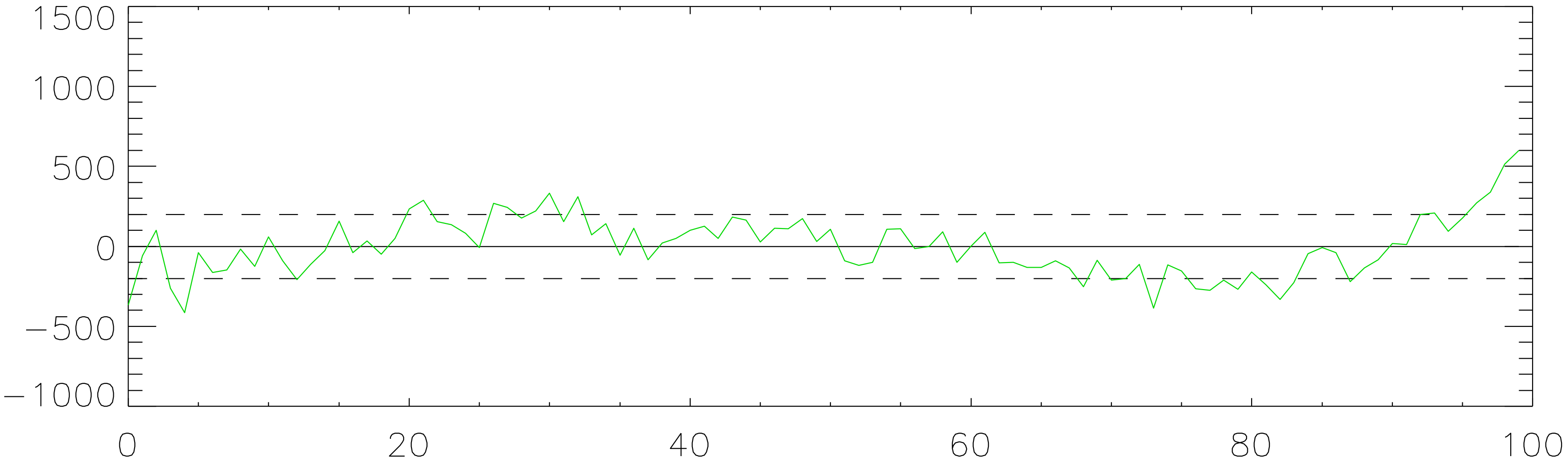




4: The SIR code

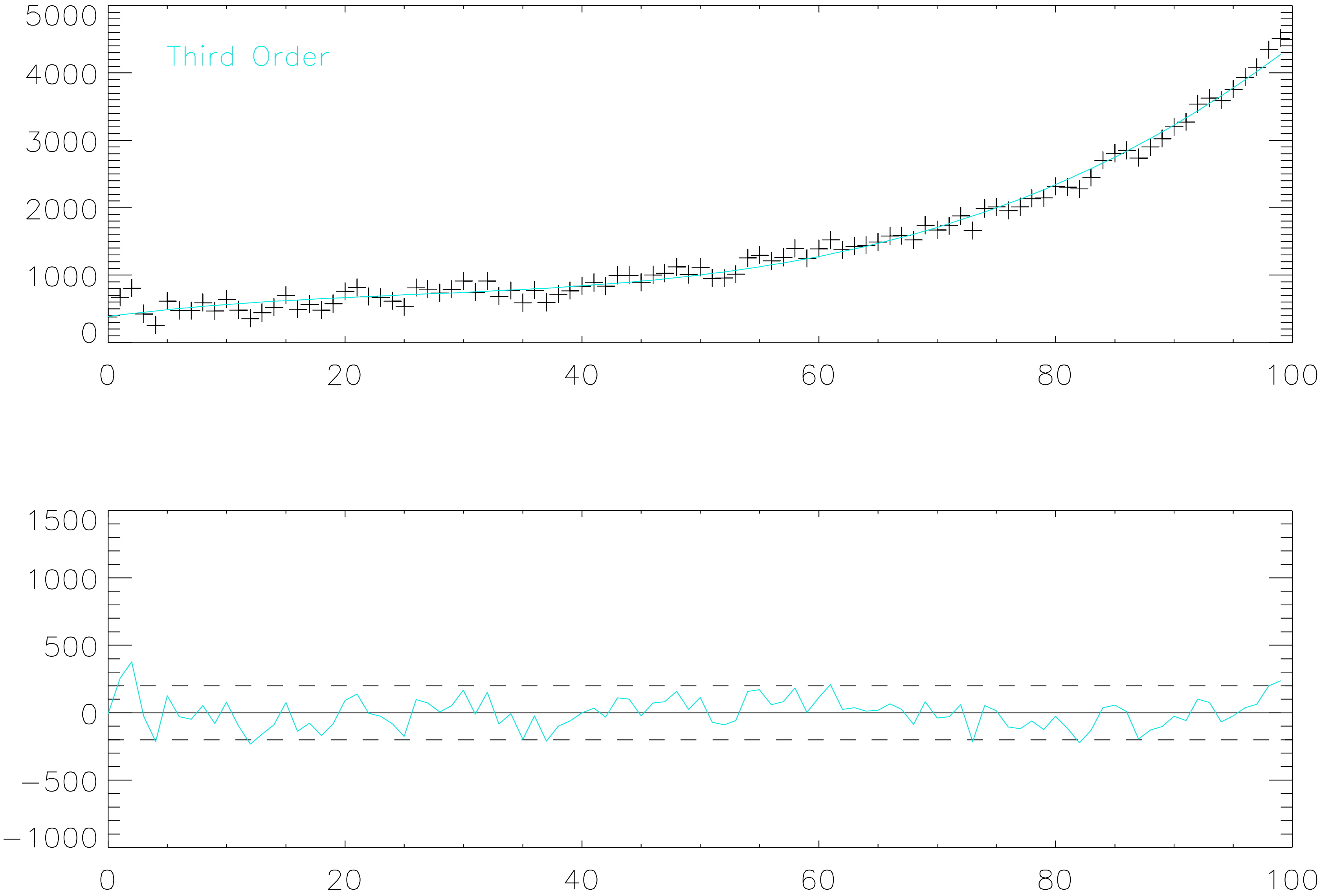
Unicity?





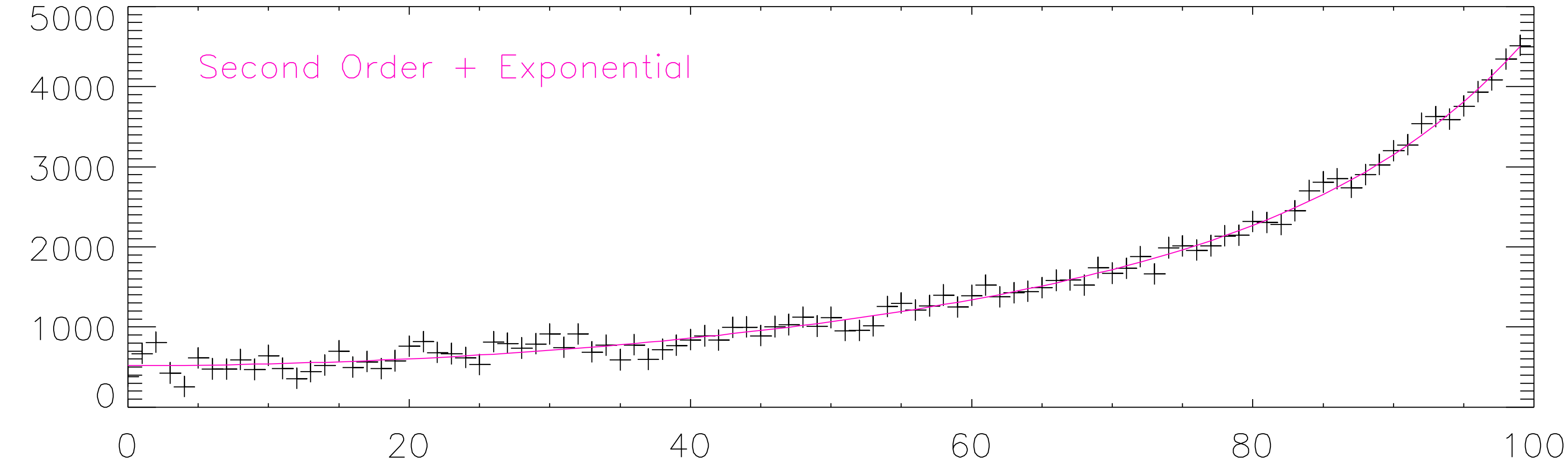
4: The SIR code

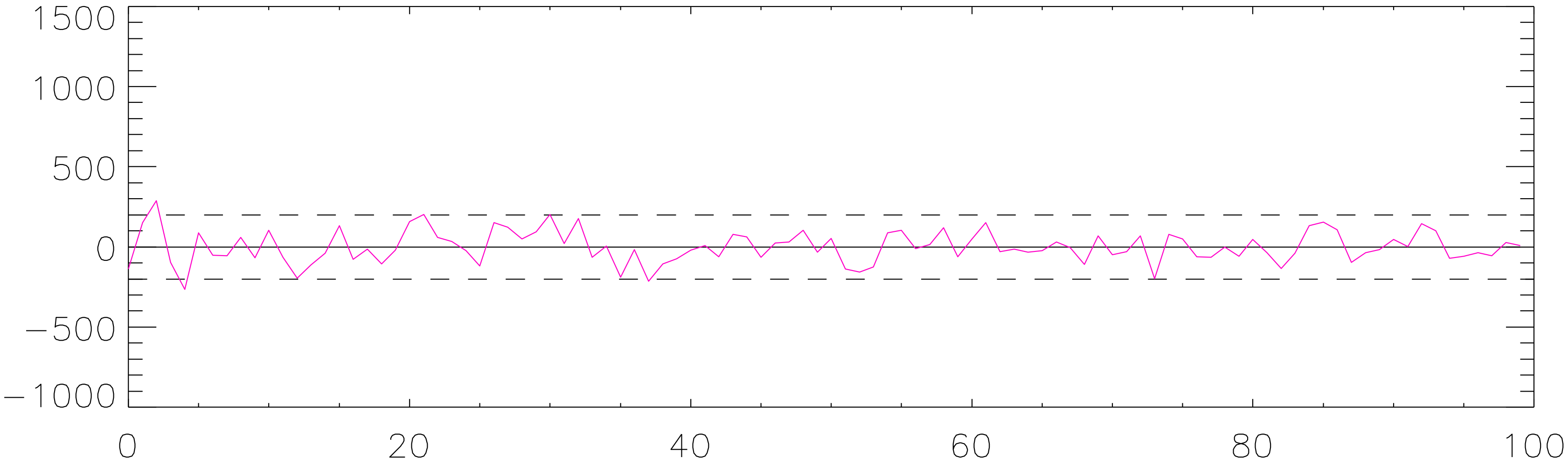
Unicity?

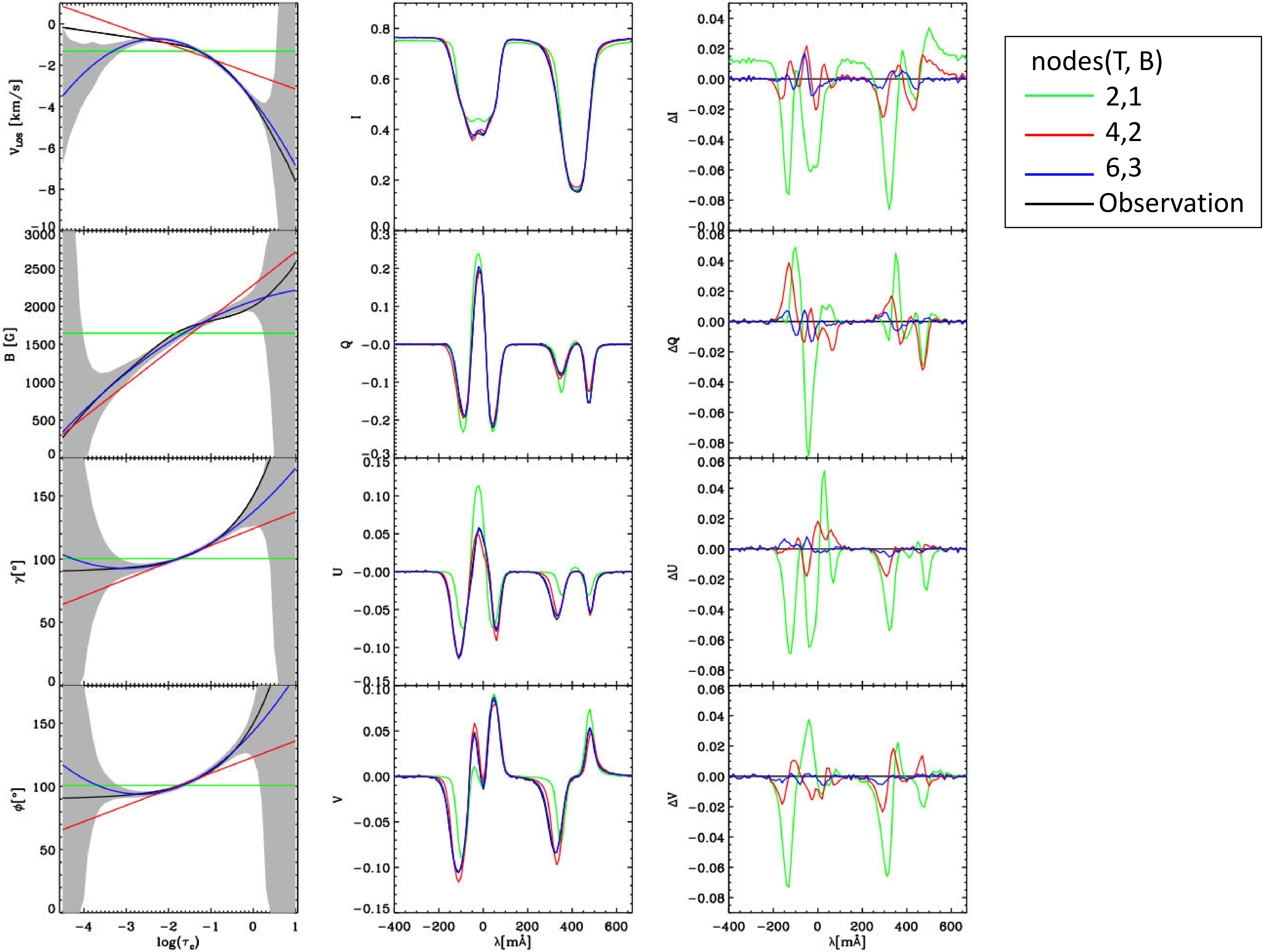


4: The SIR code

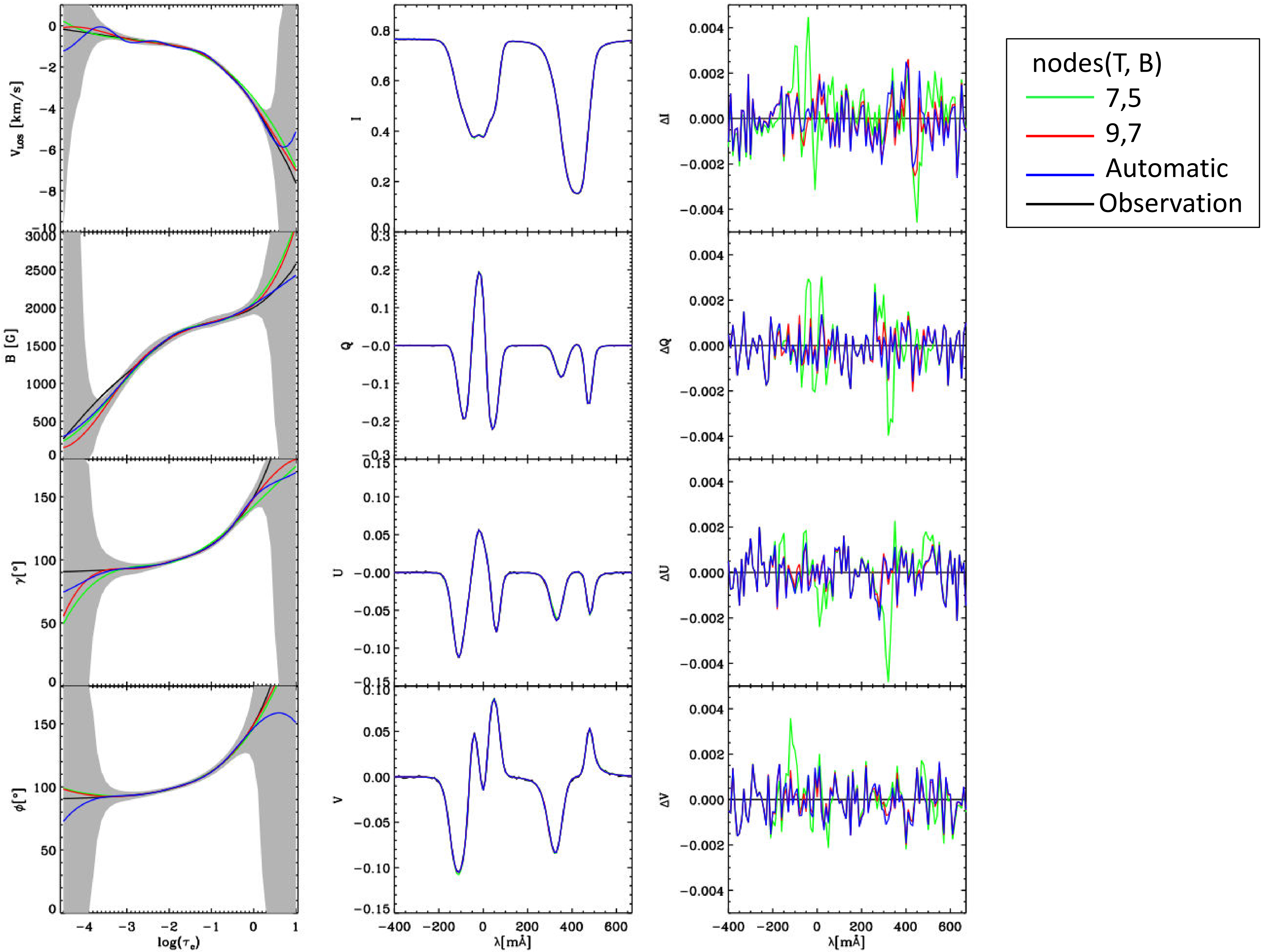
Unicity?







nodes(T, B)
2,1
4,2
6,3
Observation
V_{LOS} [km/s]
B [G]
γ[°]
ϕ[°]
$\log(\tau_c)$
I
Q
U
V
ΔI
ΔQ
ΔU
ΔV
λ[mÅ]


nodes(T, B)
7,5
9,7
Automatic
Observation
v_{LOS} [km/s]
B [G]
γ[°]
ϕ[°]
log(τ_c)
I
Q
U
V
λ[mÅ]
ΔI
ΔQ
ΔU
ΔV

5: How to choose an inversion technique?

Some Reviews:

- Socas Navarro (2001) ASP Conf Series 236, 487
- del Toro Iniesta (2003) Astronomische Nachrichten 324, 383
- Bellot Rubio (2006) ASP Conf Series, 358, 107
- Ruiz Cobo (2007) 'Modern Solar Facilities', Göttingen
- Asensio Ramos et al (2012) ApJ 748, 83
- del Toro Iniesta & Ruiz Cobo (2016) Livings Reviews in Solar Physics, 13,4

5: How to choose an inversion technique?

Constant quantities			
KPNO	Harvey et al. (1972)	LM	
HAO-KPNO	Auer et al. (1977)	LM	
Florence	Landolfi et al. (1984)	LM	✓
HAO-ASP	Skumanich et al. (1985)	LM	✓
IAC MISMA	Sánchez Almeida (1997)	LM	✓
CSIRO-Meudon	Rees et al. (2000)	PCA	✓
HAO MELANIE	Socas-Navarro et al. (2001)	LM	✓
HAO FATIMA	Socas-Navarro et al. (2001)	PCA	✓
AIP ANN	Carroll and Staude (2001)	ANN	
HAO He I D_3	López Ariste and Casini (2003)	PCA	✓
HAO ANN	Socas-Navarro (2003)	ANN	
MPS HELIx	Lagg et al. (2004)	GA	✓
IAC Molecular	Asensio Ramos (2004)	LM	
IAA MILOS	Orozco Suárez and del Toro Iniesta (2007)	LM	✓
IAC HAZEL	Asensio Ramos et al. (2008)	LM	✓
HAO VFISV	Borrero et al. (2011)	LM	✓
IAC Sparse	Asensio Ramos and de la Cruz Rodríguez (2015)	GD	✓

LM Levenberg–Marquardt, *ANN* artificial neural networks, *GA* genetic algorithm, *B* Bayesian, *GD* gradient descent

5: How to choose an inversion technique?

Variable quantities			
ETH Flux tube	Keller et al. (1990)	LM	
IAC SIR	Ruiz Cobo and del Toro Iniesta (1992)	LM	✓
ETH IT	Solanki et al. (1992b)	LM	
IAC Flux tube	Bellot Rubio et al. (1997)	LM	✓
ETH SPINOR	Frutiger and Solanki (1998)	LM	✓
IAC NLTE	Socas-Navarro et al. (2000)	LM	
HAO LILIA	Socas-Navarro (2001)	LM	✓
HAO-IAC NICOLE	Socas-Navarro (2001)	LM	✓
KIS SIRGAUS	Bellot Rubio (2003)	LM	✓
IAA SIRJUMP	Louis et al. (2009)	LM	✓
IAC Bayes	Asensio Ramos et al. (2009)	B	✓
MPS Spatially coupled	van Noort (2012)	LM	✓
IAC Regularization	Ruiz Cobo and Asensio Ramos (2013)	LM	✓

LM Levenberg–Marquardt, *ANN* artificial neural networks, *GA* genetic algorithm, *B* Bayesian, *GD* gradient descent

5: How to choose an inversion technique?

People usually select an inversion method for strange reasons: if the code is available, if it is easier or faster than others, (or was written for my boss), etc., instead of selecting the most convenient for each specific problem.

I classify available IT in 3 families:

1. ME must be used in case in which you do not know the physics controlling the line formation, or you have few wavelength points for each pixel.
2. PCA when you need fast results.
3. SIR (or similar) when you believe that your knowledge of the formation of the lines used is appropriate (and/or you be plenty of time or you be… a little crazy.)

5: How to choose an inversion technique?

1. ME family

- Advantages:
  - Fast (a typical map takes ~ hr).
  - Simple use & easy interpretation of results.
  - Robust & reliable.
  - HE, LTE etc approximations <u>are not needed</u>.
- Shortcoming:
  - Unable to fit asymmetric Stokes profiles. (but: robust against noise)
  - No gradients. (but: even theoreticians understand the results)
  - No temperature, pressure & density information. (but: no physics knowledge is required)
  - The number of free parameter grows with the number of spectral lines (but: no excuses!)

5: How to choose an inversion technique?

2. SIR family

- Advantages:
  - Arbitrarily complex along line of sight (gradients, multicomponents, etc)
  - Thermodynamic information.
  - Adaptation to many geometries & scenarios.
  - LTE/NLTE, HE, mass conservation etc.
  - Uncertainties estimation.
- Shortcoming:
  - Slow (20-30 times slower than ME)
    (but: new SIR version –upcoming soon!!- will nearly reach ME rates)
  - Difficult use
    (but: for simplified problems –like only linear stratifications-- is straightforward)
  - Unicity
    (but: only if you are ambitious)

5: How to choose an inversion technique?

3. PCA family

- Look-up-table inversion method, based in PCA
- Since 2004 used in THEMIS for real-time inversions

- Advantages: - extremely fast (one order of magnitude faster than ME)
  - simple use, robust & reliable

- Shortcoming: - few free parameter determination (ME)
  - slightly more inaccurate that ME inversions

5: How to choose an inversion technique?

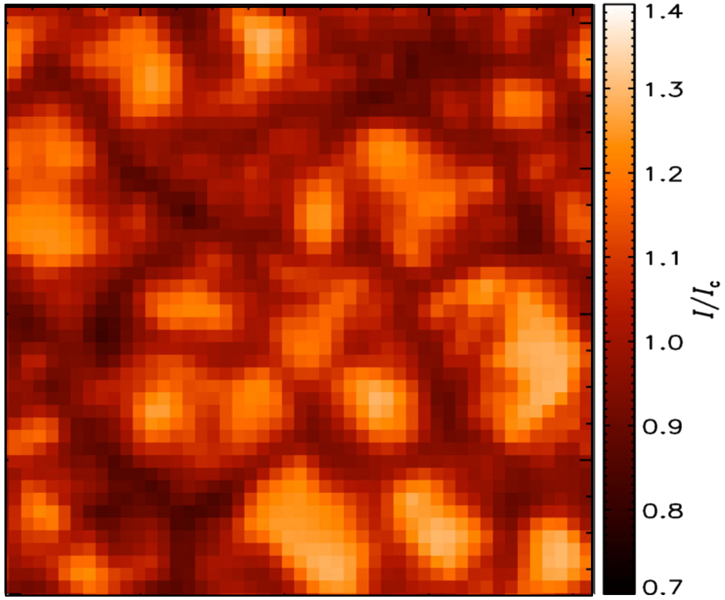
Conclusions

1. ME must be used in case in which you do not know the physics controlling the line formation or few spectral points, and you need fast results.
2. PCA when you need extremely fast results.
3. SIR (or similar) when you believe that your knowledge of the formation of the lines used is appropriate.

5: How to choose an inversion technique?

ME inversions of high-spatial resolution profiles

MHD simulations (Vögler et al. 2005)

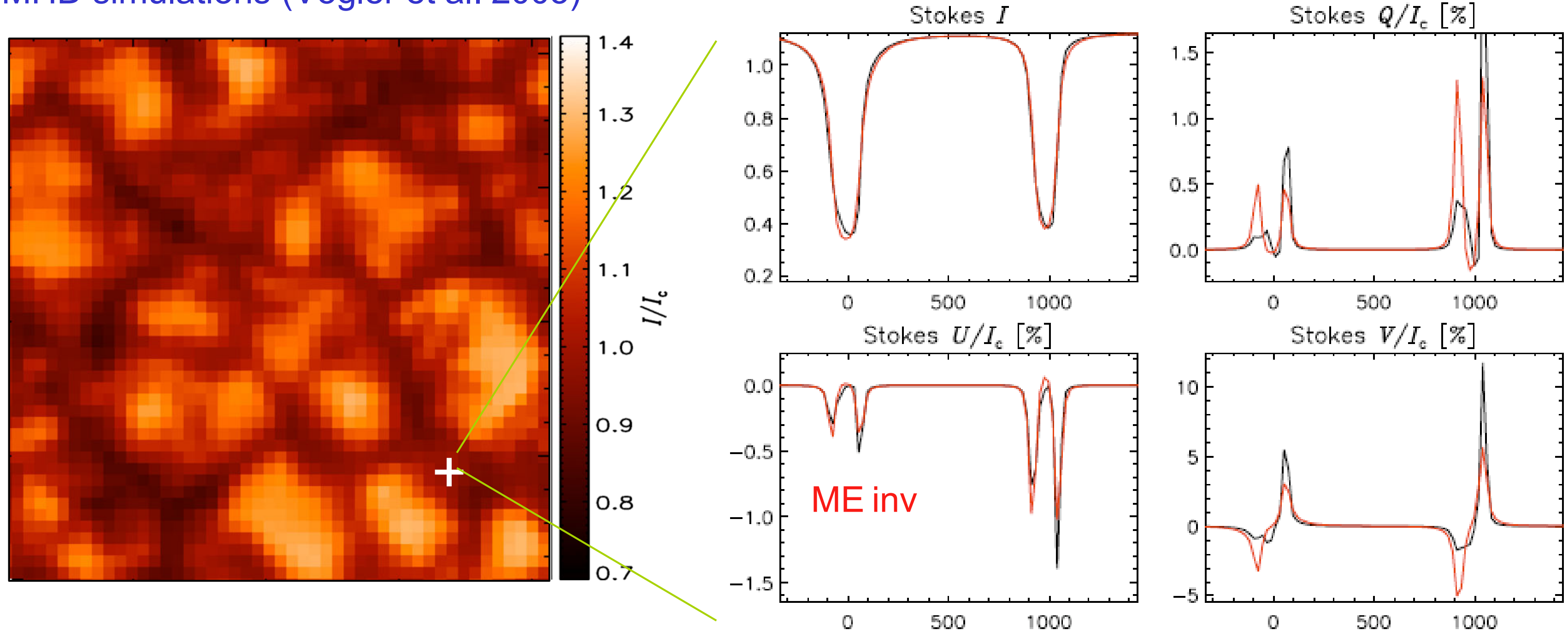


- Fe I 630.1 and 630.2 nm profiles degraded to Hinode/SP resolution and pixel size

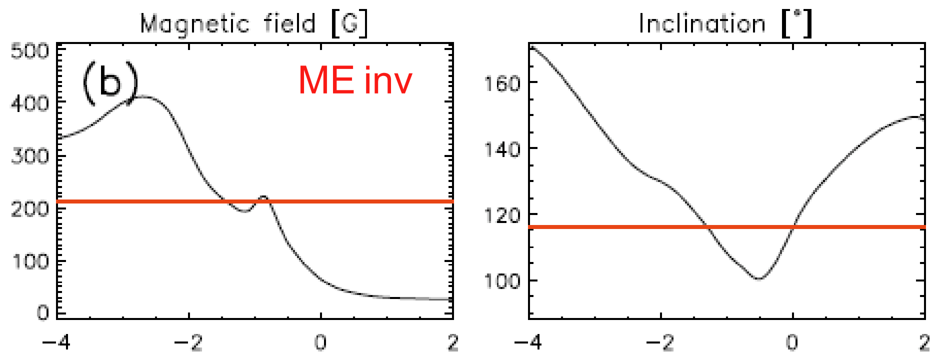
5: How to choose an inversion technique?

ME inversions of high-spatial resolution profiles

MHD simulations (Vögler et al. 2005)



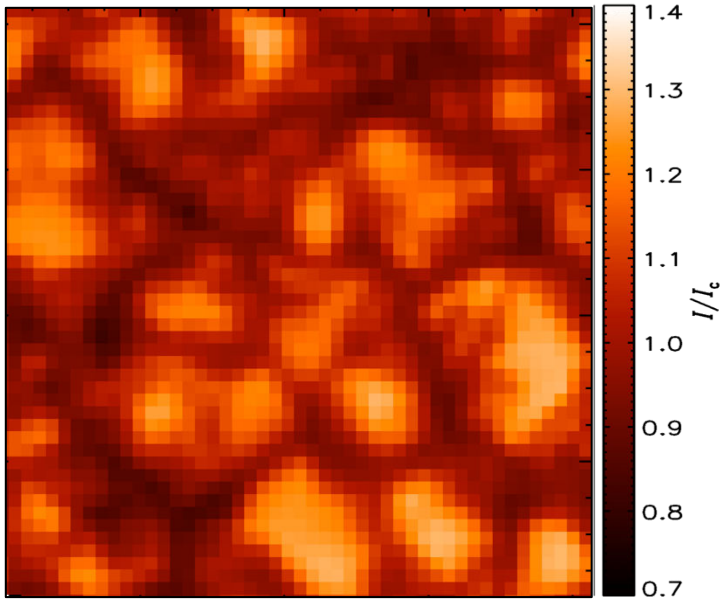
- Profiles reasonably well fitted
- ME results are some kind of "average" of physical parameters along the LOS

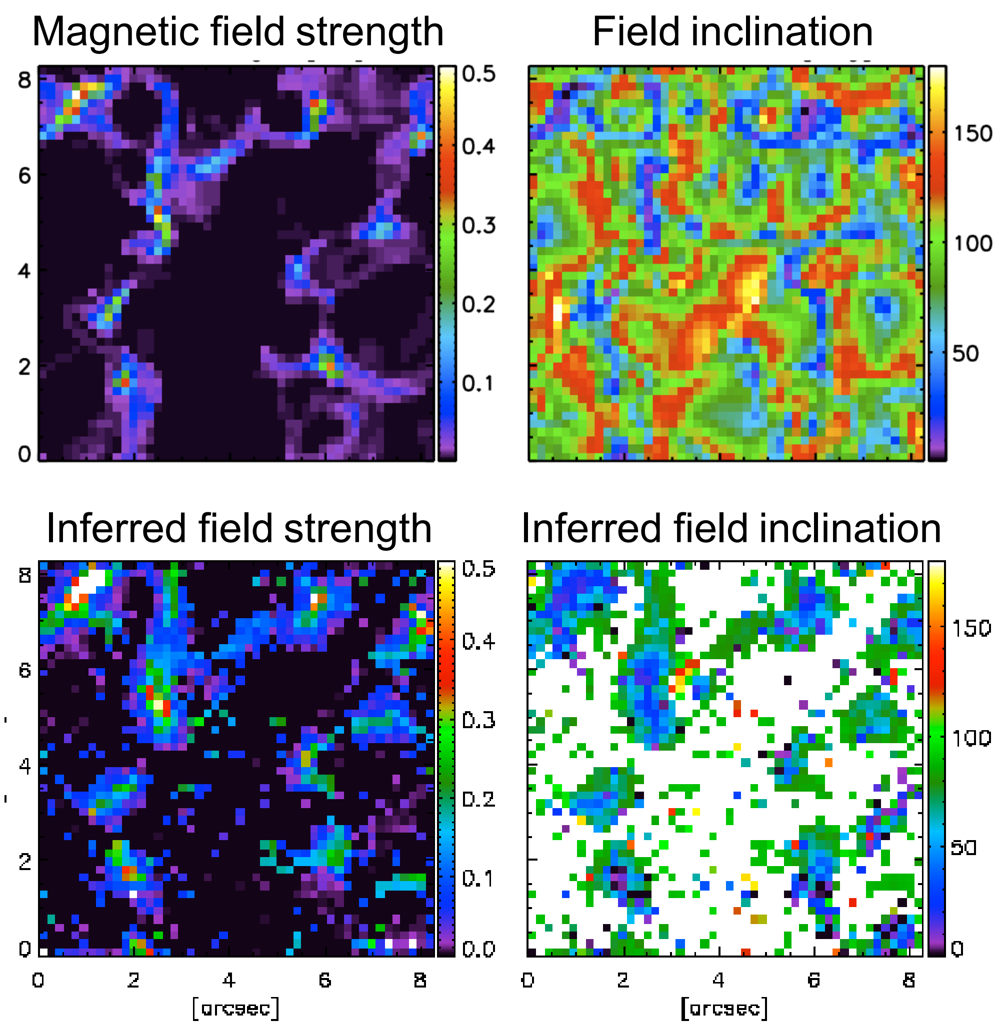


5: How to choose an inversion technique?

ME inversions of high-spatial resolution profiles

MHD simulations (Vögler et al. 2005)



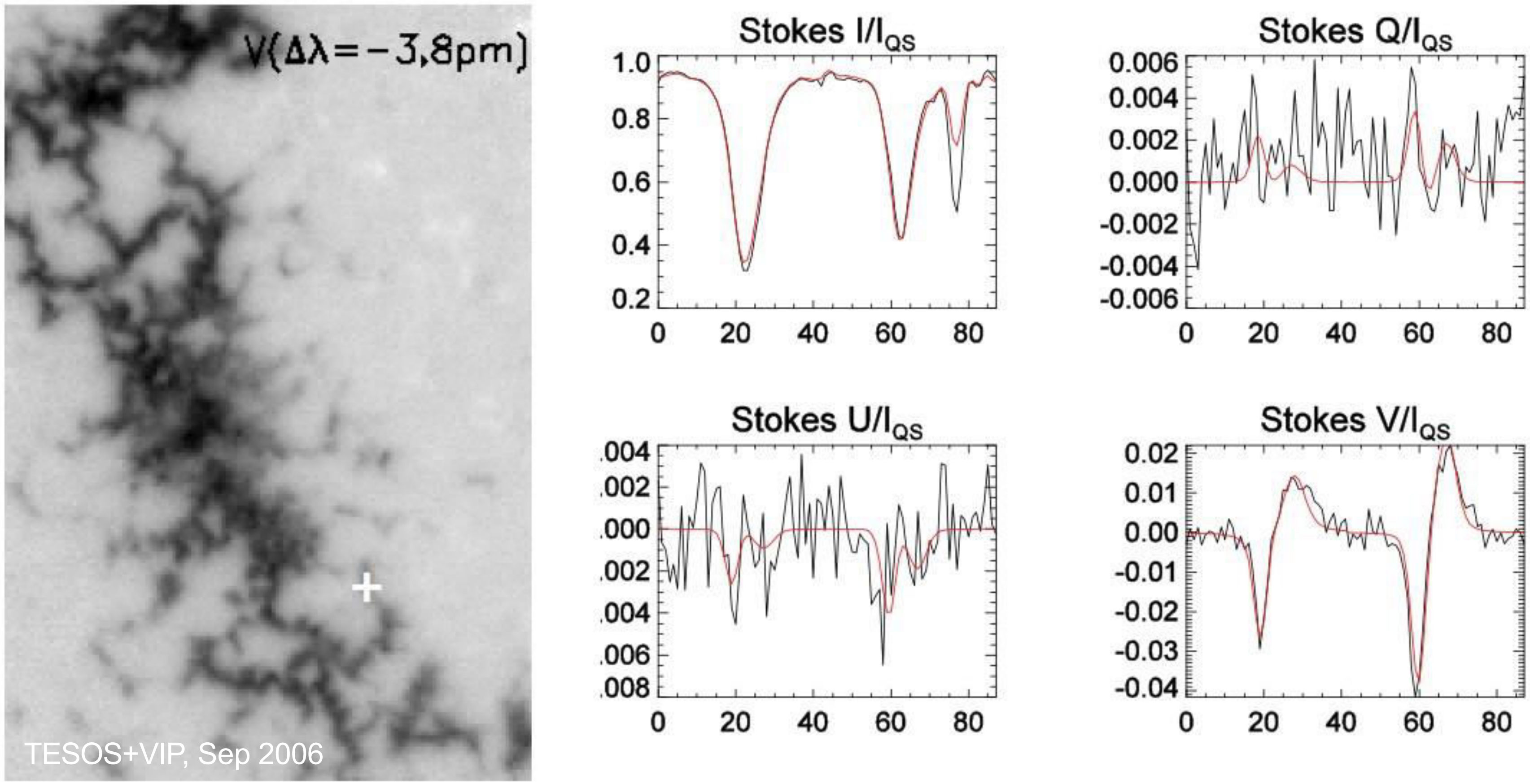


- Atmospheric parameters from MHD simulation at log τ = -2
- Maps of inferred B and γ similar to real ones!

Orozco Suárez et al. 2007, ApJ, 662, L31

5: How to choose an inversion technique?

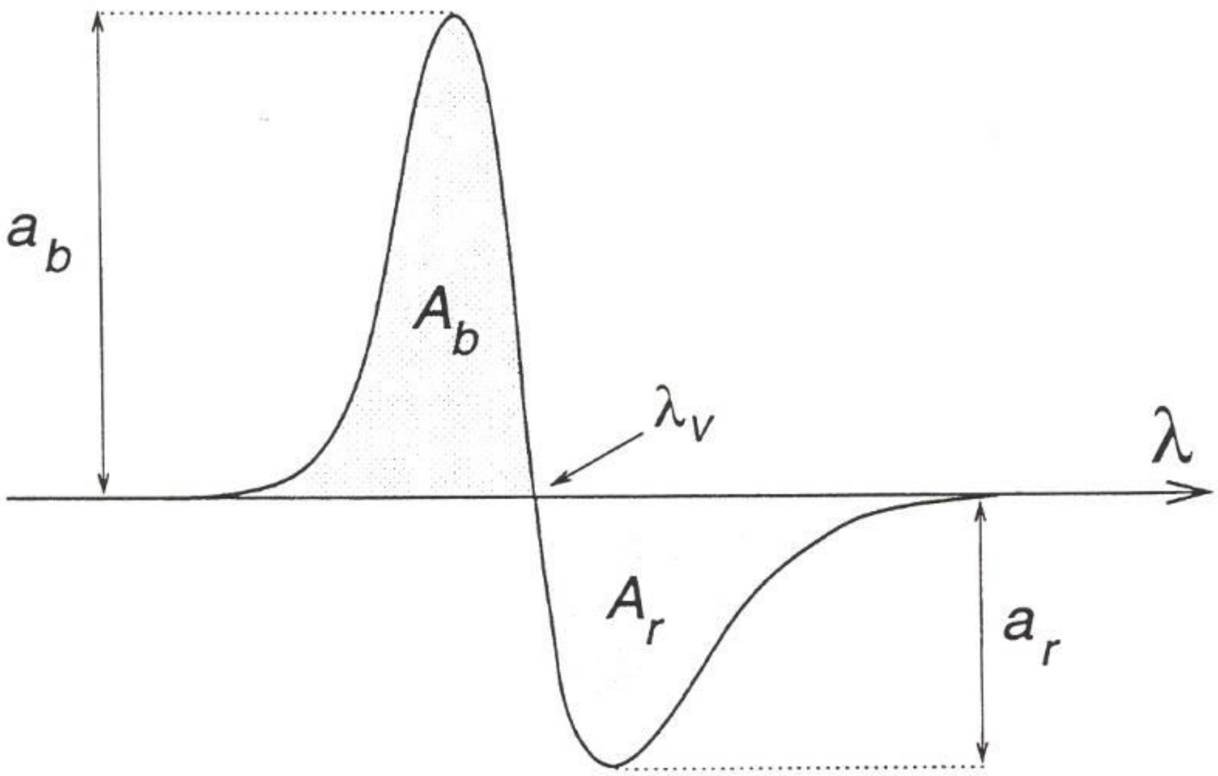
Asymmetric Stokes profiles



- KIS/IAA Visible Imaging Polarimeter + TESOS + KAOS
- VTT, Observatorio del Teide
- Spatial resolution: ~0.4"

5: How to choose an inversion technique?

Asymmetric Stokes profiles



$$\delta a \equiv \frac{a_{\mathrm{b}} - a_{\mathrm{r}}}{a_{\mathrm{b}} + a_{\mathrm{r}}}, \quad \delta A \equiv \frac{A_{\mathrm{b}} - A_{\mathrm{r}}}{A_{\mathrm{b}} + A_{\mathrm{r}}},$$

5: How to choose an inversion technique?

Asymmetric Stokes profiles

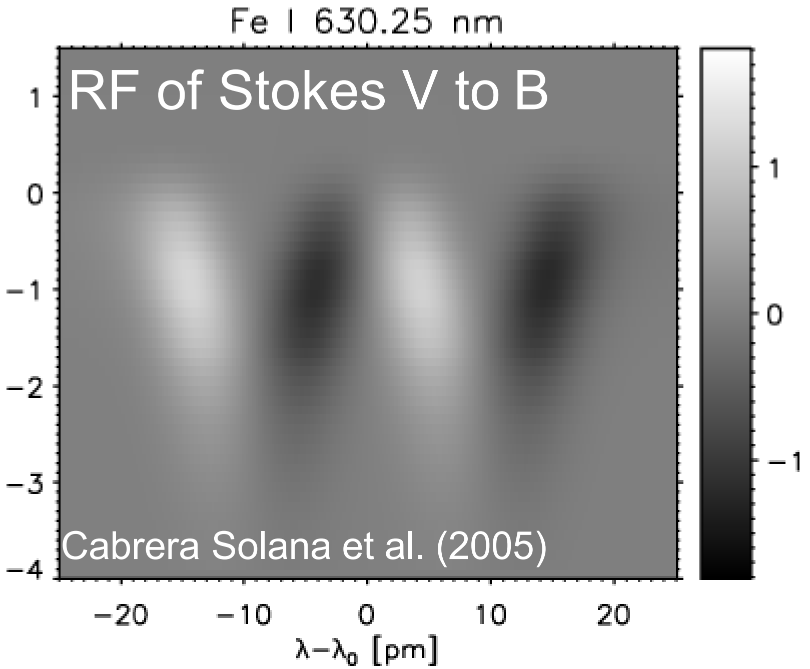
Amplitude asymmetry/
Multi-lobed Stokes profiles

Different magnetic atmospheres coexisting in resolution element

Area asymmetry

Gradients/discontinuities of B **and** v_{LOS} along LOS

Auer & Heasley (1978)



The area asymmetry gives information on the height variation of atmospheric parameters

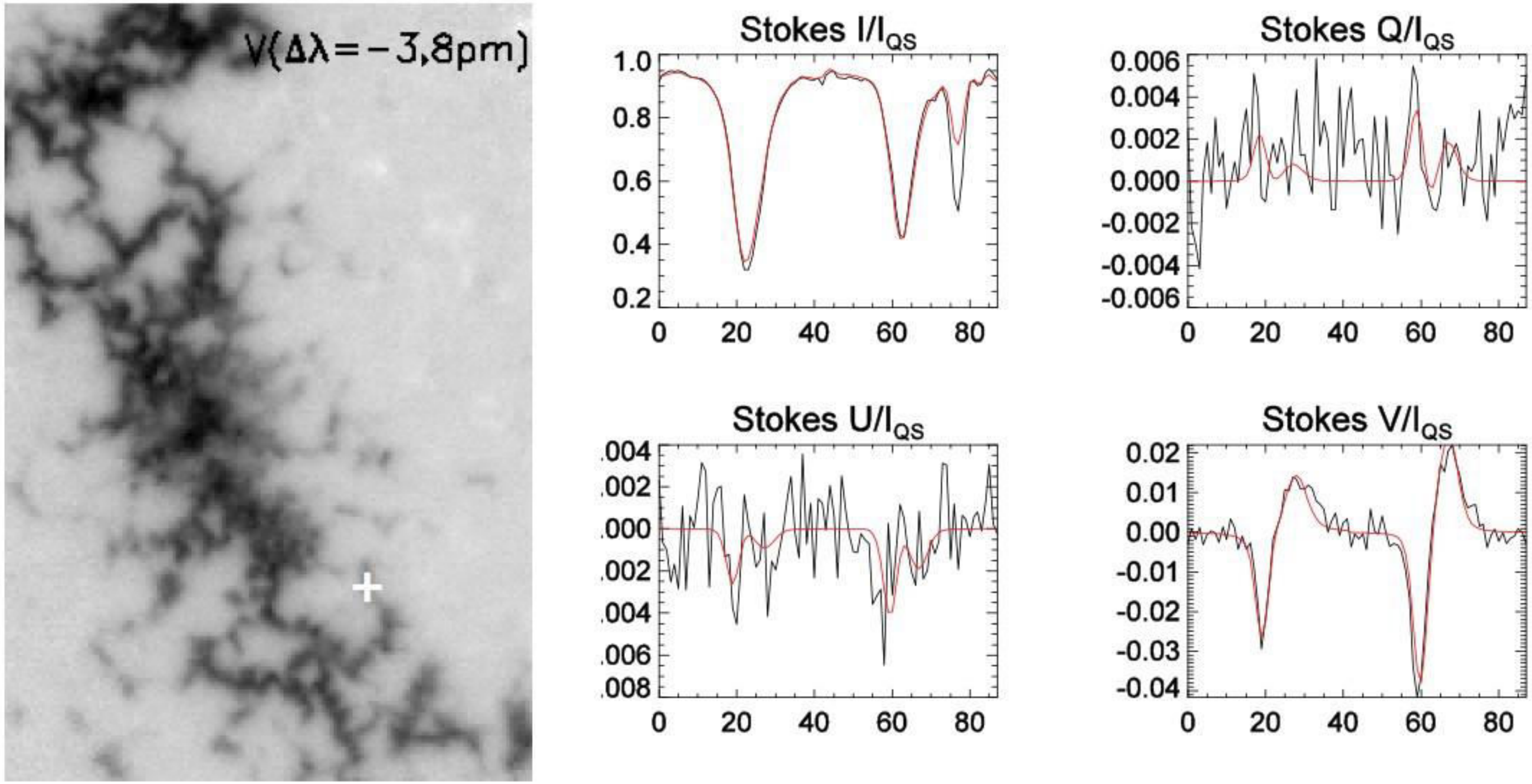
5: How to choose an inversion technique?

Asymmetric Stokes profiles

- Inversion codes capable of dealing with asymmetries
  - Are based on numerical solution of RTE
  - Provide reliable thermal information
  - (Can) use *less free parameters than ME* codes
  - Infer stratifications of physical parameters with depth

5: How to choose an inversion technique?

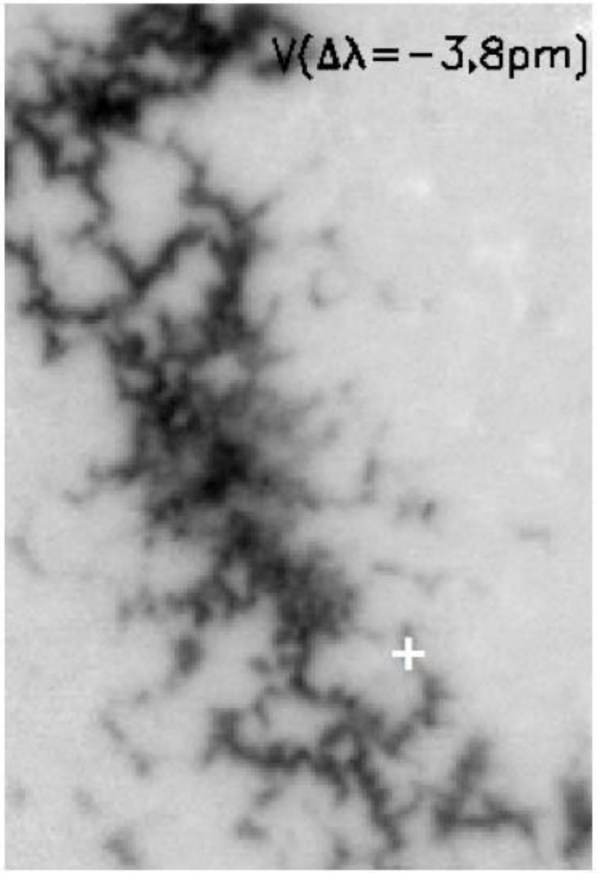
Asymmetric Stokes profiles

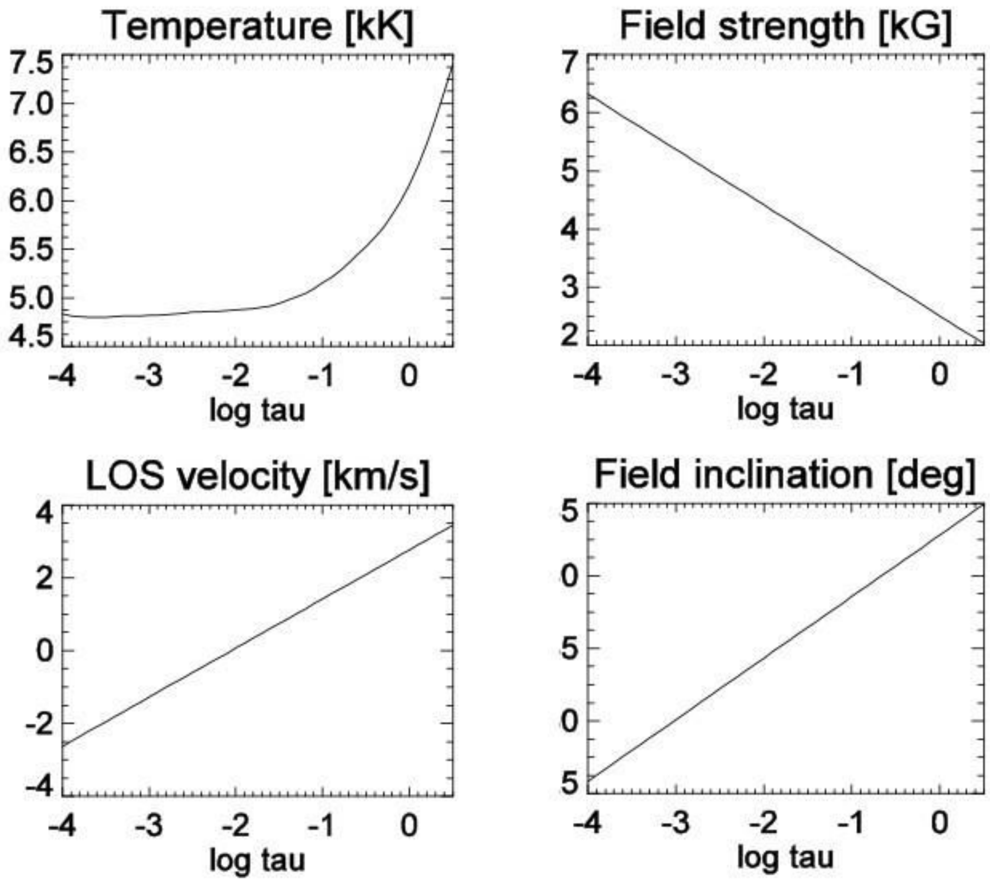


- VIP + TESOS + KAOS
- SIR with 10 free parameters
- Bellot Rubio et al. (2007)

5: How to choose an inversion technique?

Asymmetric Stokes profiles



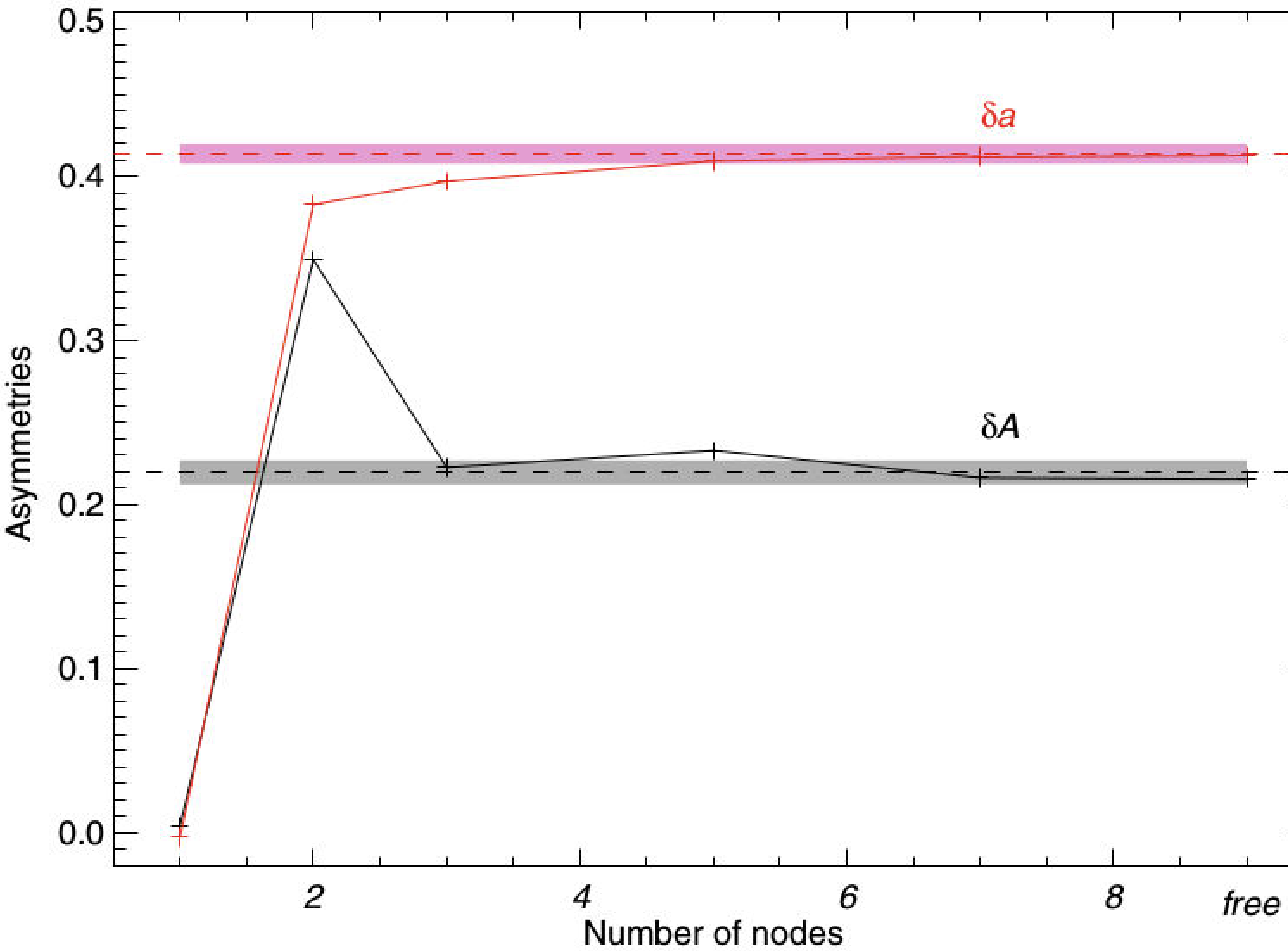


- VIP + TESOS + KAOS
- SIR with 10 free parameters
- Bellot Rubio et al. (2007)

5: How to choose an inversion technique?

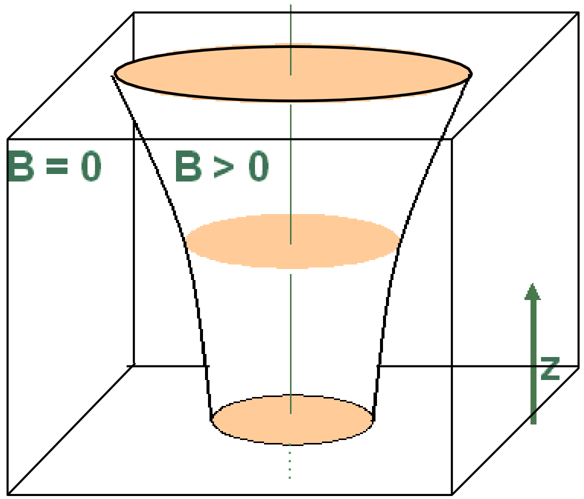
Asymmetric Stokes profiles

$$\delta a \equiv \frac{a_{\mathrm{b}} - a_{\mathrm{r}}}{a_{\mathrm{b}} + a_{\mathrm{r}}}, \quad \delta A \equiv \frac{A_{\mathrm{b}} - A_{\mathrm{r}}}{A_{\mathrm{b}} + A_{\mathrm{r}}},$$

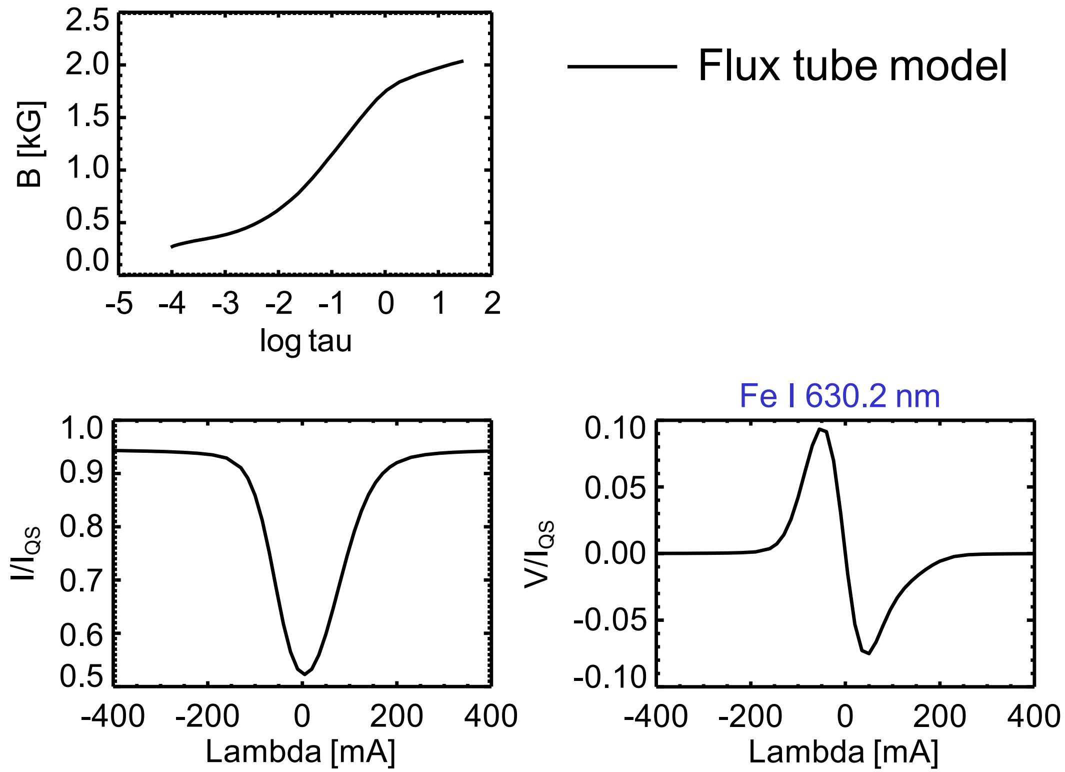


5: How to choose an inversion technique?
Asymmetric Stokes profiles

- The results change if the physical model is changed
  - Too simplistic models; often they cannot describe the real atmosphere
  - BUT: we get information about the magnetic structure of the atmosphere!



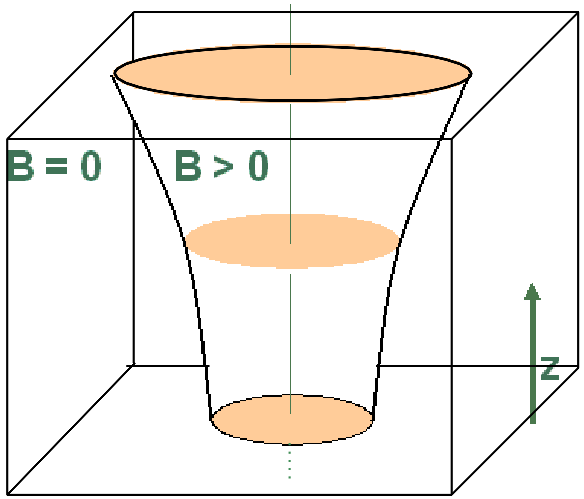
Magnetic flux tubes in facular regions



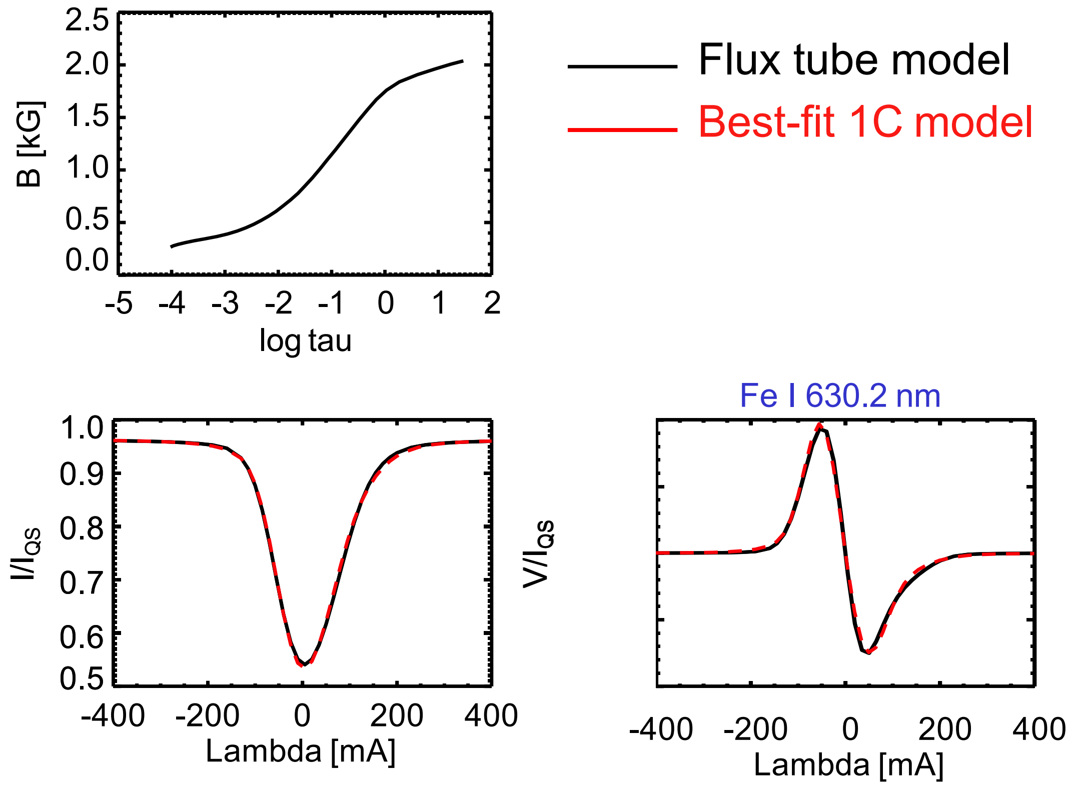
5: How to choose an inversion technique?

Asymmetric Stokes profiles

- The results change if the physical model is changed
  - Too simplistic models; often they cannot describe the real atmosphere
  - BUT: we get information about the magnetic structure of the atmosphere!

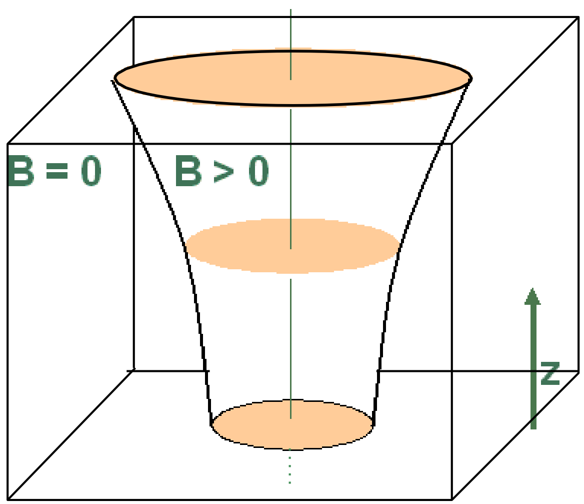


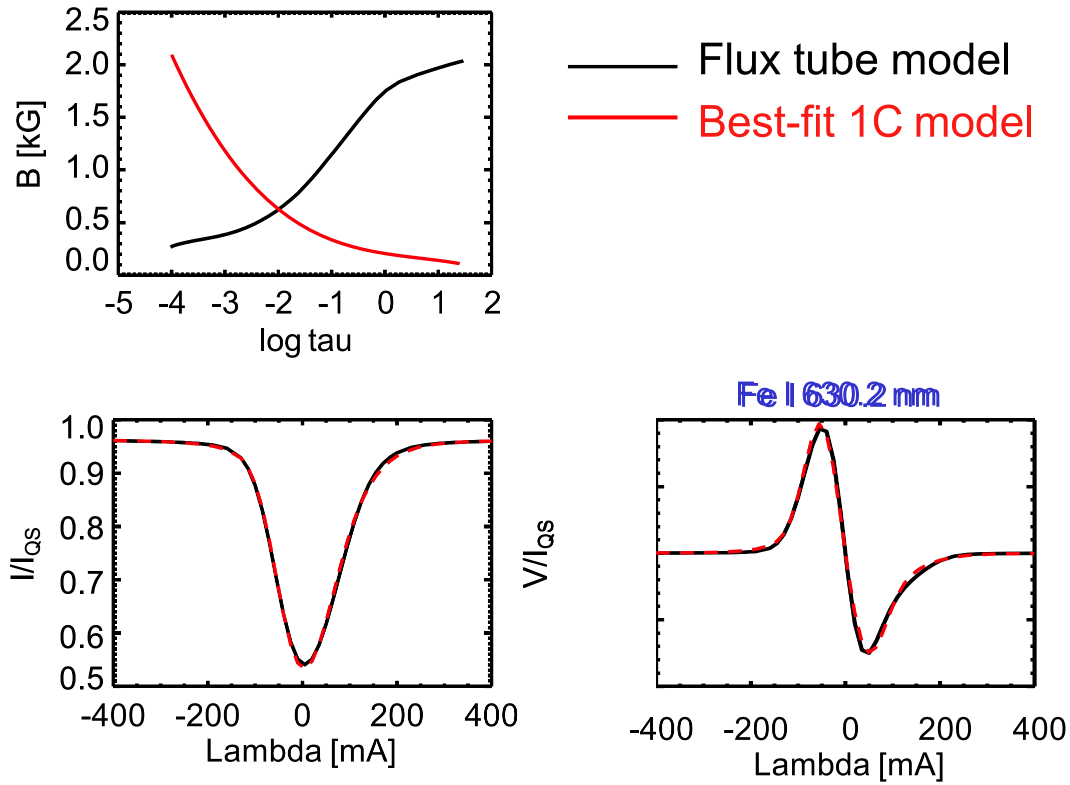
Magnetic flux tubes in facular regions



5: How to choose an inversion technique?
Asymmetric Stokes profiles

- The results change if the physical model is changed
  - Too simplistic models; often they cannot describe the real atmosphere
  - BUT: we get information about the magnetic structure of the atmosphere!





Luis Bellot Rubio

Running SIR: input files

- In the downloaded folders you can find a manual, in which it is described the menu, i.e. all the input/output formats and options for running SIR

- Running a ME code is like have a dinner in Botswana: fast, unique & sure

- Running SIR is like have a dinner in America: slow, a lot of freedom, but never know…

Running SIR: input files

All the program is control by a control file: [ ].trol

```
emacs@orion.iaa.es
File  Edit  Options  Buffers  Tools  Help

Number of cycles          (*):1              ! (0=synthesis)
Observed profiles         (*):perfil.per     !
Stray light file             :               ! (none=no stray light contam)
PSF file                     :               ! (none=no convolution with PSF)
Wavelength grid file      (s):malla.grid     ! (none=automatic selection)
Atomic parameters file       :LINES          ! (none=DEFAULT LINES file)
Abundances file              :THEVENIN       ! (none=DEFAULT ABUNDANCES file)
Initial guess model 1     (*):guess.mod      !
Initial guess model 2        :
Weight for Stokes I          :1              ! (DEFAULT=1; 0=not inverted)
Weight for Stokes Q          :4              ! (DEFAULT=1; 0=not inverted)
Weight for Stokes U          :4              ! (DEFAULT=1; 0=not inverted)
Weight for Stokes V          :4              ! (DEFAULT=1; 0=not inverted)
AUTOMATIC SELECT. OF NODES?  :0              ! (DEFAULT=0=no; 1=yes)
Nodes for temperature 1      :2
Nodes for electr. press. 1   :
Nodes for microturb. 1       :1
Nodes for magnetic field 1   :1
Nodes for LOS velocity 1     :1
Nodes for gamma 1            :1
Nodes for phi 1              :1
Invert macroturbulence 1?    :1              ! (0 or blank=no, 1=yes)
Nodes for temperature 2      :
Nodes for electr. press. 2   :
Nodes for microturb. 2       :
Nodes for magnetic field 2   :
Nodes for LOS velocity 2     :
Nodes for gamma 2            :
Nodes for phi 2              :
Invert macroturbulence 2?    :               ! (0 or blank=no, 1=yes)
Invert filling factor?       :               ! (0 or blank=no, 1=yes)
Invert stray light factor?   :               ! (0 or blank=no, 1=yes)
mu=cos (theta)               :0.64           ! (DEFAULT: mu=1. mu<0 => West)
Estimated S/N for I          :200            ! (DEFAULT: 1000)
Continuum contrast           :               ! (DEFAULT: not used)
Tolerance for SVD            :               ! (DEFAULT value: 1e-4)
Initial diagonal element     :               ! (DEFAULT value: 1.e-3)
Splines/Linear Interpolation :               ! (0 or blank=splines, 1=linear)
Gas pressure at surface 1    :               ! (0 or blank=Pe boundary cond.)
Gas pressure at surface 2    :               ! (0 or blank=Pe boundary cond.)
Magnetic pressure term?      :0              ! (0 or blank=no, 1=yes)
NLTE Departures filename     :               ! blanck= LTE (Ej. depart_6494.dat'
--:**  sir.trol         (Text Fill)--L1--C0--Top-----------------------------
```

Number of cycles:

0 : Synthesis Mode
-1: Evaluate Response Function at every depth
-2: Evaluate Response Function at the nodes
>0: Number of cycles of the inversion

Running SIR: input files

emacs@orion.iaa.es

File Edit Options Buffers Tools Help

```
Number of cycles          (*):1          ! (0=synthesis)
Observed profiles         (*):perfil.per !
Stray light file             :           ! (none=no stray light contam)
PSF file                     :           ! (none=no convolution with PSF)
Wavelength grid file      (s):malla.grid ! (none=automatic selection)
Atomic parameters file       :LINES      ! (none=DEFAULT LINES file)
Abundances file              :THEVENIN   ! (none=DEFAULT ABUNDANCES file)
Initial guess model 1     (*):guess.mod  !
Initial guess model 2        :
Weight for Stokes I          :1          ! (DEFAULT=1; 0=not inverted)
Weight for Stokes Q          :4          ! (DEFAULT=1; 0=not inverted)
Weight for Stokes U          :4          ! (DEFAULT=1; 0=not inverted)
Weight for Stokes V          :4          ! (DEFAULT=1; 0=not inverted)
AUTOMATIC SELECT. OF NODES?  :0          ! (DEFAULT=0=no; 1=yes)
Nodes for temperature 1      :2
Nodes for electr. press. 1   :
Nodes for microturb. 1       :1
Nodes for magnetic field 1   :1
Nodes for LOS velocity 1     :1
Nodes for gamma 1            :1
Nodes for phi 1              :1
Invert macroturbulence 1?    :1          ! (0 or blank=no, 1=yes)
Nodes for temperature 2      :
Nodes for electr. press. 2   :
Nodes for microturb. 2       :
Nodes for magnetic field 2   :
Nodes for LOS velocity 2     :
Nodes for gamma 2            :
Nodes for phi 2              :
Invert macroturbulence 2?    :           ! (0 or blank=no, 1=yes)
Invert filling factor?       :           ! (0 or blank=no, 1=yes)
Invert stray light factor?   :           ! (0 or blank=no, 1=yes)
mu=cos (theta)               :0.64       ! (DEFAULT: mu=1. mu<0 => West)
Estimated S/N for I          :200        ! (DEFAULT: 1000)
Continuum contrast           :           ! (DEFAULT: not used)
Tolerance for SVD            :           ! (DEFAULT value: 1e-4)
Initial diagonal element     :           ! (DEFAULT value: 1.e-3)
Splines/Linear Interpolation :           ! (0 or blank=splines, 1=linear)
Gas pressure at surface 1    :           ! (0 or blank=Pe boundary cond.)
Gas pressure at surface 2    :           ! (0 or blank=Pe boundary cond.)
Magnetic pressure term?      :0          ! (0 or blank=no, 1=yes)
NLTE Departures filename     :           ! blanck= LTE (Ej. depart_6494.dat'
--:**  sir.trol        (Text Fill)--L1--C0--Top------------------------------
```

Profile file: [ ].per

emacs@orion.iaa.es

File Edit Options Buffers Tools Help

```
    1.00000    -583.463    0.744716  0.000127651  -0.00144671  -0.00170201
    1.00000    -561.933    0.745056  0.000340403  -0.00153181  -0.00165946
    1.00000    -540.403    0.744716  0.000127651  -0.00157436  -0.00174456
    1.00000    -518.873    0.748843   0.00246792 -0.000765906  -0.00178711
    1.00000    -497.343    0.745269  0.000127651 -0.000170201  -0.00251047
    1.00000    -475.813    0.747226 -0.000723356  0.000638255  -0.00187221
    1.00000    -454.283    0.733653   0.00102121   0.00170201  -0.00272322
    1.00000    -432.753    0.740121   0.00212752  -0.00195732  -0.00276577
    1.00000    -411.223    0.735525  0.000170201  0.000936107  -0.00221262
    1.00000    -389.693    0.742163 -0.000765906   0.00140416  -0.00199987
    1.00000    -368.163    0.734802  0.000680805   0.00102121  -0.00399973
    1.00000    -346.633    0.739014   0.00204242   0.00221262  -0.00659530
    1.00000    -325.103    0.729611  0.000723356   0.00276577  -0.00531879
    1.00000    -303.573    0.737951  0.000638255 -8.51007e-05  -0.00714846
    1.00000    -282.043    0.723824 -8.51007e-05 -0.000340403   -0.0123821
    1.00000    -260.513    0.727994  -0.00127651 -0.000510604  -0.00804201
    1.00000    -238.983    0.706846 -0.000468054  0.000765906   -0.0117439
    1.00000    -217.453    0.700123 -0.000510604  -0.00314873   -0.0152756
    1.00000    -195.923    0.702464  -0.00408483  -0.00297852   -0.0265514
    1.00000    -174.393    0.678252  0.000638255 -0.000765906   -0.0284236
    1.00000    -152.863    0.660679  -0.00276577  -0.00497839   -0.0282534
    1.00000    -131.333    0.637872  -0.00527624  -0.00259557   -0.0340403
    1.00000    -109.803    0.624213  -0.00399973  -0.00195732   -0.0439545
    1.00000    -88.2730    0.576983  -0.00472309 -0.000468054   -0.0545495
    1.00000    -66.7430    0.542261  -0.00421248  -0.00408483   -0.0738248
    1.00000    -45.2130    0.488776  -0.00182966  -0.00425503    -0.100972
    1.00000    -23.6830    0.404739  -0.00672295   -0.0135310    -0.146373
    1.00000    -2.15300    0.351679  -0.00923342   -0.0158713    -0.161393
    1.00000     19.3770    0.303214   -0.0100419   -0.0198710    -0.136459
    1.00000     40.9070    0.259472   -0.0120843  -0.00851007   -0.0844624
    1.00000     62.4370    0.237303   -0.0113184   0.00527624   -0.0372741
    1.00000     83.9670    0.256664   -0.0192328    0.0169776   -0.0101695
    1.00000     105.497    0.264961   -0.0185094    0.0184668   0.00974403
    1.00000     127.027    0.240495   -0.0143395   0.00719101    0.0344232
    1.00000     148.557    0.258706   -0.0125523  -0.00859517    0.0799521
    1.00000     170.087    0.307894   -0.0135736   -0.0171478     0.145863
    1.00000     191.617    0.375719  -0.00799946   -0.0212326     0.175392
    1.00000     213.147    0.432439  -0.00608470   -0.0139140     0.173350
    1.00000     234.677    0.519199   -0.0100419  -0.00578685     0.132885
    1.00000     256.207    0.576302  -0.00536134  -0.00191477    0.0843773
    1.00000     277.737    0.616980 -0.000808456  -0.00136161    0.0598258
    1.00000     299.267    0.656424  -0.00736121 -0.000255302    0.0405930
--:--  perfil.per       (Text Fill)--L1--C0--Top------------------------------
```

Line index | $\Delta\lambda$ [mA] | I/I_{qs} | Q/I_{qs} | U/I_{qs} | V/I_{qs}

read_profiles.pro

write_profiles.pro

Running SIR: input files

```
emacs@orion.iaa.es
File  Edit  Options  Buffers  Tools  Help
Number of cycles          (*):1          ! (0=synthesis)
Observed profiles         (*):perfil.per !
Stray light file             :           ! (none=no stray light contam)
PSF file                     :           ! (none=no convolution with PSF)
Wavelength grid file      (s):malla.grid ! (none=automatic selection)
Atomic parameters file       :LINES      ! (none=DEFAULT LINES file)
Abundances file              :THEVENIN   ! (none=DEFAULT ABUNDANCES file)
Initial guess model 1     (*):guess.mod  !
Initial guess model 2        :
Weight for Stokes I          :1          ! (DEFAULT=1; 0=not inverted)
Weight for Stokes Q          :4          ! (DEFAULT=1; 0=not inverted)
Weight for Stokes U          :4          ! (DEFAULT=1; 0=not inverted)
Weight for Stokes V          :4          ! (DEFAULT=1; 0=not inverted)
AUTOMATIC SELECT. OF NODES?  :0          ! (DEFAULT=0=no; 1=yes)
Nodes for temperature 1      :2
Nodes for electr. press. 1   :
Nodes for microturb. 1       :1
Nodes for magnetic field 1   :1
Nodes for LOS velocity 1     :1
Nodes for gamma 1            :1
Nodes for phi 1              :1
Invert macroturbulence 1?    :1          ! (0 or blank=no, 1=yes)
Nodes for temperature 2      :
Nodes for electr. press. 2   :
Nodes for microturb. 2       :
Nodes for magnetic field 2   :
Nodes for LOS velocity 2     :
Nodes for gamma 2            :
Nodes for phi 2              :
Invert macroturbulence 2?    :           ! (0 or blank=no, 1=yes)
Invert filling factor?       :           ! (0 or blank=no, 1=yes)
Invert stray light factor?   :           ! (0 or blank=no, 1=yes)
mu=cos (theta)               :0.64       ! (DEFAULT: mu=1. mu<0 => West)
Estimated S/N for I          :200        ! (DEFAULT: 1000)
Continuum contrast           :           ! (DEFAULT: not used)
Tolerance for SVD            :           ! (DEFAULT value: 1e-4)
Initial diagonal element     :           ! (DEFAULT value: 1.e-3)
Splines/Linear Interpolation :           ! (0 or blank=splines, 1=linear)
Gas pressure at surface 1    :           ! (0 or blank=Pe boundary cond.)
Gas pressure at surface 2    :           ! (0 or blank=Pe boundary cond.)
Magnetic pressure term?      :0          ! (0 or blank=no, 1=yes)
NLTE Departures filename     :           ! blanck= LTE (Ej. depart_6494.dat'
--:**  sir.trol        (Text Fill)--L1--C0--Top------------------------------
```

Profile file: [ ].per

```
emacs@orion.iaa.es
File  Edit  Options  Buffers  Tools  Help
 1.00000   -583.463   0.744716  0.000127651  -0.00144671  -0.00170201
 1.00000   -561.933   0.745056  0.000340403  -0.00153181  -0.00165946
 1.00000   -540.403   0.744716  0.000127651  -0.00157436  -0.00174456
 1.00000   -518.873   0.748843   0.00246792 -0.000765906  -0.00178711
 1.00000   -497.343   0.745269  0.000127651 -0.000170201  -0.00251047
 1.00000   -475.813   0.747226 -0.000723356  0.000638255  -0.00187221
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 1.00000   -325.103   0.729611  0.000723356   0.00276577  -0.00531879
 1.00000   -303.573   0.737951  0.000638255 -8.51007e-05  -0.00714846
 1.00000   -282
 1.00000   -260
 1.00000   -238
 1.00000   -217
 1.00000   -195
 1.00000   -174
 1.00000   -152
 1.00000   -131
 1.00000   -109
 1.00000   -88.2
 1.00000   -66.7430   0.542261  -0.00421248  -0.00408483   -0.0738248
 1.00000   -45.2130   0.488776  -0.00182966  -0.00425503    -0.100972
 1.00000   -23.6830   0.404739  -0.00672295   -0.0135310    -0.146373
 1.00000   -2.15300   0.351679  -0.00923342   -0.0158713    -0.161393
 1.00000    19.3770   0.303214   -0.0100419   -0.0198710    -0.136459
 1.00000    40.9070   0.259472   -0.0120843  -0.00851007   -0.0844624
 1.00000    62.4370   0.237303   -0.0113184   0.00527624   -0.0372741
 1.00000    83.9670   0.256664   -0.0192328    0.0169776   -0.0101695
 1.00000    105.497   0.264961   -0.0185094    0.0184668   0.00974403
 1.00000    127.027   0.240495   -0.0143395   0.00719101    0.0344232
 1.00000    148.557   0.258706   -0.0125523  -0.00859517    0.0799521
 1.00000    170.087   0.307894   -0.0135736   -0.0171478     0.145863
 1.00000    191.617   0.375719  -0.00799946   -0.0212326     0.175392
 1.00000    213.147   0.432439  -0.00608470   -0.0139140     0.173350
 1.00000    234.677   0.519199   -0.0100419  -0.00578685     0.132885
 1.00000    256.207   0.576302  -0.00536134  -0.00191477    0.0843773
 1.00000    277.737   0.616980 -0.000808456  -0.00136161    0.0598258
 1.00000    299.267   0.656424  -0.00736121 -0.000255302    0.0405930
--:--  perfil.per      (Text Fill)--L1--C0--Top------------------------------
```

Values lower than -1 for any Stokes at any wavelength will not be consider in the χ^2

Line index | $\Delta\lambda$ [mA] | I/I_{qs} | Q/I_{qs} | U/I_{qs} | V/I_{qs}

read_profiles.pro

write_profiles.pro

Running SIR: input files

All the program is control by a control file:

emacs@orion.iaa.es

File Edit Options Buffers Tools Help

```
Number of cycles          (*):1          ! (0=synthesis)
Observed profiles         (*):perfil.per !
Stray light file             :           ! (none=no stray light contam)
PSF file                     :           ! (none=no convolution with PSF)
Wavelength grid file      (s):malla.grid ! (none=automatic selection)
Atomic parameters file       :LINES      ! (none=DEFAULT LINES file)
Abundances file              :THEVENIN   ! (none=DEFAULT ABUNDANCES file)
Initial guess model 1     (*):guess.mod  !
Initial guess model 2        :
Weight for Stokes I          :1          ! (DEFAULT=1; 0=not inverted)
Weight for Stokes Q          :4          ! (DEFAULT=1; 0=not inverted)
Weight for Stokes U          :4          ! (DEFAULT=1; 0=not inverted)
Weight for Stokes V          :4          ! (DEFAULT=1; 0=not inverted)
AUTOMATIC SELECT. OF NODES?  :0          ! (DEFAULT=0=no; 1=yes)
Nodes for temperature 1      :2
Nodes for electr. press. 1   :
Nodes for microturb. 1       :1
Nodes for magnetic field 1   :1
Nodes for LOS velocity 1     :1
Nodes for gamma 1            :1
Nodes for phi 1              :1
Invert macroturbulence 1?    :1          ! (0 or blank=no, 1=yes)
Nodes for temperature 2      :
Nodes for electr. press. 2   :
Nodes for microturb. 2       :
Nodes for magnetic field 2   :
Nodes for LOS velocity 2     :
Nodes for gamma 2            :
Nodes for phi 2              :
Invert macroturbulence 2?    :           ! (0 or blank=no, 1=yes)
Invert filling factor?       :           ! (0 or blank=no, 1=yes)
Invert stray light factor?   :           ! (0 or blank=no, 1=yes)
mu=cos (theta)               :0.64       ! (DEFAULT: mu=1. mu<0 => West)
Estimated S/N for I          :200        ! (DEFAULT: 1000)
Continuum contrast           :           ! (DEFAULT: not used)
Tolerance for SVD            :           ! (DEFAULT value: 1e-4)
Initial diagonal element     :           ! (DEFAULT value: 1.e-3)
Splines/Linear Interpolation :           ! (0 or blank=splines, 1=linear)
Gas pressure at surface 1    :           ! (0 or blank=Pe boundary cond.)
Gas pressure at surface 2    :           ! (0 or blank=Pe boundary cond.)
Magnetic pressure term?      :0          ! (0 or blank=no, 1=yes)
NLTE Departures filename     :           ! blanck= LTE (Ej. depart_6494.dat'
--:** sir.trol        (Text Fill)--L1--C0--Top----------------------------------
```

Stray light file: The file (with the same format as a profile file) containing the stray light contamination

Stray-light considerations

- Stray-light in 1C inversions:
  - $I_{obs} = (1-\alpha)\, I_1 + \alpha\, I_{stray}$
  - Accounts for both stray light and/or magnetic filling factor

- Stray-light in 2C inversions:
  - It is NOT equivalent to a magnetic filling factor
  - SIR has two free parameters: a and f
  - $I_{obs} = (1-\alpha)\, [f\, I_1 + (1-f)\, I_2] + \alpha\, I_{stray}$

- Global vs local stray-light profile
  - Classical treatment: global stray-light profile (average over FOV)
  - Orozco Suárez et al. (2007): local stray-light profile accounts for telescope diffraction

- Previous deconvolution of the spatial PSF

Running SIR: input files

All the program is control by a control file:

```
emacs@orion.iaa.es
File  Edit  Options  Buffers  Tools  Help

Number of cycles          (*):1          ! (0=synthesis)
Observed profiles         (*):perfil.per !
Stray light file             :           ! (none=no stray light contam)
PSF file                     :           ! (none=no convolution with PSF)
Wavelength grid file      (s):malla.grid ! (none=automatic selection)
Atomic parameters file       :LINES      ! (none=DEFAULT LINES file)
Abundances file              :THEVENIN   ! (none=DEFAULT ABUNDANCES file)
Initial guess model 1     (*):guess.mod  !
Initial guess model 2        :
Weight for Stokes I          :1          ! (DEFAULT=1; 0=not inverted)
Weight for Stokes Q          :4          ! (DEFAULT=1; 0=not inverted)
Weight for Stokes U          :4          ! (DEFAULT=1; 0=not inverted)
Weight for Stokes V          :4          ! (DEFAULT=1; 0=not inverted)
AUTOMATIC SELECT. OF NODES?  :0          ! (DEFAULT=0=no; 1=yes)
Nodes for temperature 1      :2
Nodes for electr. press. 1   :
Nodes for microturb. 1       :1
Nodes for magnetic field 1   :1
Nodes for LOS velocity 1     :1
Nodes for gamma 1            :1
Nodes for phi 1              :1
Invert macroturbulence 1?    :1          ! (0 or blank=no, 1=yes)
Nodes for temperature 2      :
Nodes for electr. press. 2   :
Nodes for microturb. 2       :
Nodes for magnetic field 2   :
Nodes for LOS velocity 2     :
Nodes for gamma 2            :
Nodes for phi 2              :
Invert macroturbulence 2?    :           ! (0 or blank=no, 1=yes)
Invert filling factor?       :           ! (0 or blank=no, 1=yes)
Invert stray light factor?   :           ! (0 or blank=no, 1=yes)
mu=cos (theta)               :0.64       ! (DEFAULT: mu=1. mu<0 => West)
Estimated S/N for I          :200        ! (DEFAULT: 1000)
Continuum contrast           :           ! (DEFAULT: not used)
Tolerance for SVD            :           ! (DEFAULT value: 1e-4)
Initial diagonal element     :           ! (DEFAULT value: 1.e-3)
Splines/Linear Interpolation :           ! (0 or blank=splines, 1=linear)
Gas pressure at surface 1    :           ! (0 or blank=Pe boundary cond.)
Gas pressure at surface 2    :           ! (0 or blank=Pe boundary cond.)
Magnetic pressure term?      :0          ! (0 or blank=no, 1=yes)
NLTE Departures filename     :           ! blanck= LTE (Ej. depart_6494.dat'

--:**  sir.trol        (Text Fill)--L1--C0--Top------------------------------------
```

PSF file: A two column file containing:

1. wavelength (in mA respect of the center of the line)
2. the PSF

Running SIR: input files

```
Number of cycles          (*):1          ! (0=synthesis)
Observed profiles         (*):perfil.per !
Stray light file             :           ! (none=no stray light contam)
PSF file                     :           ! (none=no convolution with PSF)
Wavelength grid file      (s):malla.grid ! (none=automatic selection)
Atomic parameters file       :LINES      ! (none=DEFAULT LINES file)
Abundances file              :THEVENIN   ! (none=DEFAULT ABUNDANCES file)
Initial guess model 1     (*):guess.mod  !
Initial guess model 2        :
Weight for Stokes I          :1          ! (DEFAULT=1; 0=not inverted)
Weight for Stokes Q          :4          ! (DEFAULT=1; 0=not inverted)
Weight for Stokes U          :4          ! (DEFAULT=1; 0=not inverted)
Weight for Stokes V          :4          ! (DEFAULT=1; 0=not inverted)
AUTOMATIC SELECT. OF NODES?  :0          ! (DEFAULT=0=no; 1=yes)
Nodes for temperature 1      :2
Nodes for electr. press. 1   :
Nodes for microturb. 1       :1
Nodes for magnetic field 1   :1
Nodes for LOS velocity 1     :1
Nodes for gamma 1            :1
Nodes for phi 1              :1
Invert macroturbulence 1?    :1          ! (0 or blank=no, 1=yes)
Nodes for temperature 2      :
Nodes for electr. press. 2   :
Nodes for microturb. 2       :
Nodes for magnetic field 2   :
Nodes for LOS velocity 2     :
Nodes for gamma 2            :
Nodes for phi 2              :
Invert macroturbulence 2?    :           ! (0 or blank=no, 1=yes)
Invert filling factor?       :           ! (0 or blank=no, 1=yes)
Invert stray light factor?   :           ! (0 or blank=no, 1=yes)
mu=cos (theta)               :0.64       ! (DEFAULT: mu=1. mu<0 => West)
Estimated S/N for I          :200        ! (DEFAULT: 1000)
Continuum contrast           :           ! (DEFAULT: not used)
Tolerance for SVD            :           ! (DEFAULT value: 1e-4)
Initial diagonal element     :           ! (DEFAULT value: 1.e-3)
Splines/Linear Interpolation :           ! (0 or blank=splines, 1=linear)
Gas pressure at surface 1    :           ! (0 or blank=Pe boundary cond.)
Gas pressure at surface 2    :           ! (0 or blank=Pe boundary cond.)
Magnetic pressure term?      :0          ! (0 or blank=no, 1=yes)
NLTE Departures filename     :           ! blanck= LTE (Ej. depart_6494.dat'
--:** sir.trol        (Text Fill)--L1--C0--Top---------------------------------
```

Wavelength grid file

```
IMPORTANT: a) All items must be separated by commas.
           b) The first six characters of the last line
              in the header (if any) must contain the symbol ---

Line and blends indices   :  Initial lambda     Step     Final lambda
(in this order)                  (mA)           (mA)         (mA)
-----------------------------------------------------------------------
1,2                       :     -645.9,        21.53,      1743.93
--:--  malla.grid        (Text Fill)--L7--C17--All---------------------
```

Basilio Ruiz Cobo

Running SIR: input files

```
Number of cycles          (*):1          ! (0=synthesis)
Observed profiles         (*):perfil.per !
Stray light file             :           ! (none=no stray light contam)
PSF file                     :           ! (none=no convolution with PSF)
Wavelength grid file      (s):malla.grid ! (none=automatic selection)
Atomic parameters file       :LINES      ! (none=DEFAULT LINES file)
Abundances file              :THEVENIN   ! (none=DEFAULT ABUNDANCES file)
Initial guess model 1     (*):guess.mod  !
Initial guess model 2        :
Weight for Stokes I          :1          ! (DEFAULT=1; 0=not inverted)
Weight for Stokes Q          :4          ! (DEFAULT=1; 0=not inverted)
Weight for Stokes U          :4          ! (DEFAULT=1; 0=not inverted)
Weight for Stokes V          :4          ! (DEFAULT=1; 0=not inverted)
AUTOMATIC SELECT. OF NODES?  :0          ! (DEFAULT=0=no; 1=yes)
Nodes for temperature 1      :2
Nodes for electr. press. 1   :
Nodes for microturb. 1       :1
Nodes for magnetic field 1   :1
Nodes for LOS velocity 1     :1
Nodes for gamma 1            :1
Nodes for phi 1              :1
Invert macroturbulence 1?    :1          ! (0 or blank=no, 1=yes)
Nodes for temperature 2      :
Nodes for electr. press. 2   :
Nodes for microturb. 2       :
Nodes for magnetic field 2   :
Nodes for LOS velocity 2     :
Nodes for gamma 2            :
Nodes for phi 2              :
Invert macroturbulence 2?    :           ! (0 or blank=no, 1=yes)
Invert filling factor?       :           ! (0 or blank=no, 1=yes)
Invert stray light factor?   :           ! (0 or blank=no, 1=yes)
mu=cos (theta)               :0.64       ! (DEFAULT: mu=1. mu<0 => West)
Estimated S/N for I          :200        ! (DEFAULT: 1000)
Continuum contrast           :           ! (DEFAULT: not used)
Tolerance for SVD            :           ! (DEFAULT value: 1e-4)
Initial diagonal element     :           ! (DEFAULT value: 1.e-3)
Splines/Linear Interpolation :           ! (0 or blank=splines, 1=linear)
Gas pressure at surface 1    :           ! (0 or blank=Pe boundary cond.)
Gas pressure at surface 2    :           ! (0 or blank=Pe boundary cond.)
Magnetic pressure term?      :0          ! (0 or blank=no, 1=yes)
NLTE Departures filename     :           ! blanck= LTE (Ej. depart_6494.dat'
--:** sir.trol        (Text Fill)--L1--C0--Top------------------------------
```

ATOMIC PARAMETER FILE

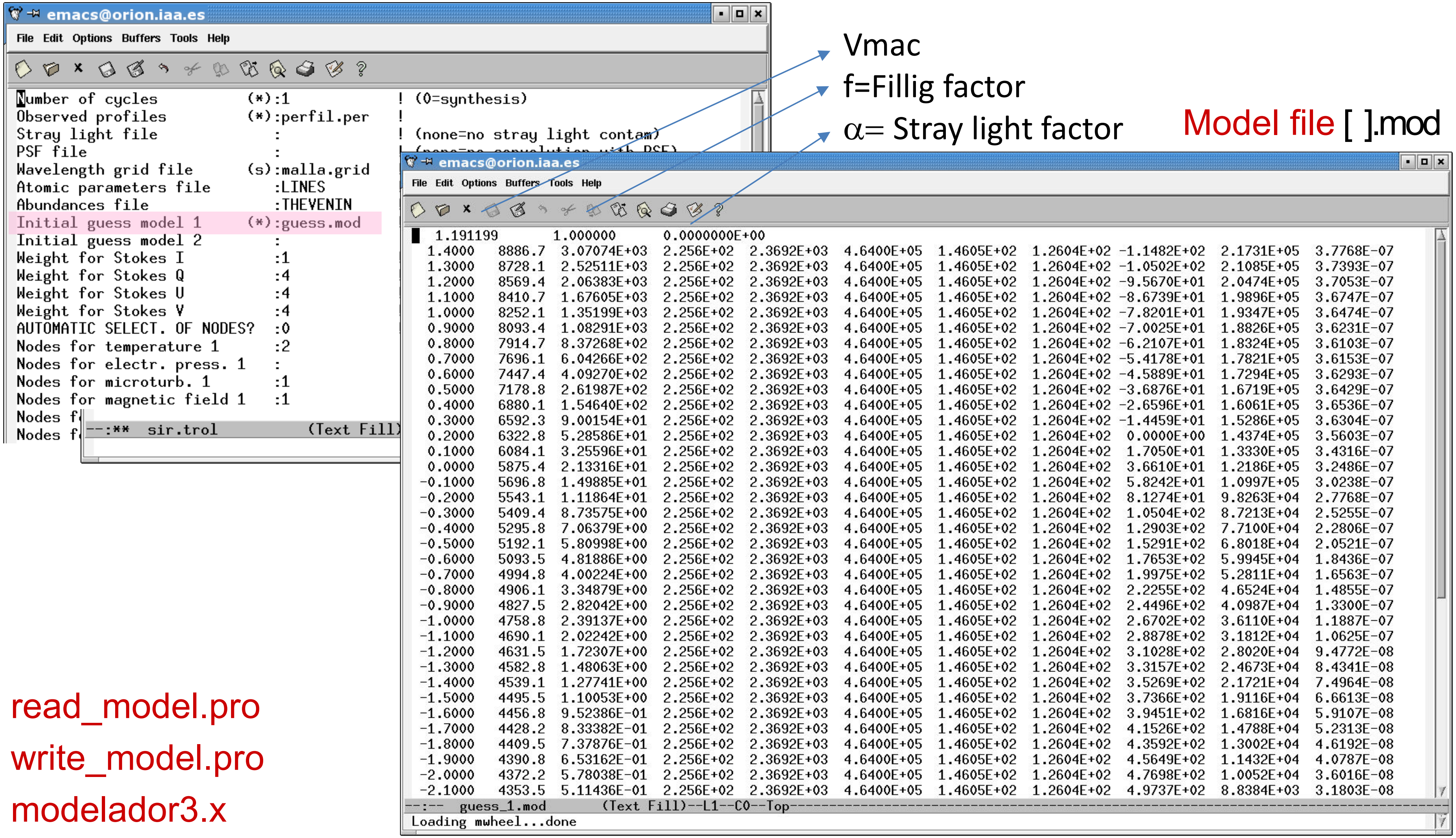
```
 1=FE 1 6301.5012    1.0  3.654  -0.75   5P 2.0- 5D 2.0  0.243  2.3520e-14
 2=FE 1 6302.4936    1.0  3.686  -1.236  5P 1.0- 5D 0.0  0.240  2.3976e-14
--:--  LINES          (Text Fill)--L3--C0--All-------------------------------
```

Line index

Atom Ion λ E

χ log gf transition Barklem's coeff.

Running SIR: input files



```
Number of cycles              (*):1          ! (0=synthesis)
Observed profiles             (*):perfil.per !
Stray light file                 :           ! (none=no stray light contam)
PSF file                         :
Wavelength grid file          (s):malla.grid
Atomic parameters file           :LINES
Abundances file                  :THEVENIN
Initial guess model 1         (*):guess.mod
Initial guess model 2            :
Weight for Stokes I              :1
Weight for Stokes Q              :4
Weight for Stokes U              :4
Weight for Stokes V              :4
AUTOMATIC SELECT. OF NODES?      :0
Nodes for temperature 1          :2
Nodes for electr. press. 1       :
Nodes for microturb. 1           :1
Nodes for magnetic field 1       :1
Nodes f
Nodes f
--:** sir.trol (Text Fill)
```

Vmac

f=Fillig factor

α= Stray light factor

Model file [ ].mod

log τ	T	P_e	v_{mic}	B	v_{LOS}	γ	φ	z [km]	P_g	ρ
1.191199	1.000000	0.0000000E+00								
1.4000	8886.7	3.07074E+03	2.256E+02	2.3692E+03	4.6400E+05	1.4605E+02	1.2604E+02	-1.1482E+02	2.1731E+05	3.7768E-07
1.3000	8728.1	2.52511E+03	2.256E+02	2.3692E+03	4.6400E+05	1.4605E+02	1.2604E+02	-1.0502E+02	2.1085E+05	3.7393E-07
1.2000	8569.4	2.06383E+03	2.256E+02	2.3692E+03	4.6400E+05	1.4605E+02	1.2604E+02	-9.5670E+01	2.0474E+05	3.7053E-07
1.1000	8410.7	1.67605E+03	2.256E+02	2.3692E+03	4.6400E+05	1.4605E+02	1.2604E+02	-8.6739E+01	1.9896E+05	3.6747E-07
1.0000	8252.1	1.35199E+03	2.256E+02	2.3692E+03	4.6400E+05	1.4605E+02	1.2604E+02	-7.8201E+01	1.9347E+05	3.6474E-07
0.9000	8093.4	1.08291E+03	2.256E+02	2.3692E+03	4.6400E+05	1.4605E+02	1.2604E+02	-7.0025E+01	1.8826E+05	3.6231E-07
0.8000	7914.7	8.37268E+02	2.256E+02	2.3692E+03	4.6400E+05	1.4605E+02	1.2604E+02	-6.2107E+01	1.8324E+05	3.6103E-07
0.7000	7696.1	6.04266E+02	2.256E+02	2.3692E+03	4.6400E+05	1.4605E+02	1.2604E+02	-5.4178E+01	1.7821E+05	3.6153E-07
0.6000	7447.4	4.09270E+02	2.256E+02	2.3692E+03	4.6400E+05	1.4605E+02	1.2604E+02	-4.5889E+01	1.7294E+05	3.6293E-07
0.5000	7178.8	2.61987E+02	2.256E+02	2.3692E+03	4.6400E+05	1.4605E+02	1.2604E+02	-3.6876E+01	1.6719E+05	3.6429E-07
0.4000	6880.1	1.54640E+02	2.256E+02	2.3692E+03	4.6400E+05	1.4605E+02	1.2604E+02	-2.6596E+01	1.6061E+05	3.6536E-07
0.3000	6592.3	9.00154E+01	2.256E+02	2.3692E+03	4.6400E+05	1.4605E+02	1.2604E+02	-1.4459E+01	1.5286E+05	3.6304E-07
0.2000	6322.8	5.28586E+01	2.256E+02	2.3692E+03	4.6400E+05	1.4605E+02	1.2604E+02	0.0000E+00	1.4374E+05	3.5603E-07
0.1000	6084.1	3.25596E+01	2.256E+02	2.3692E+03	4.6400E+05	1.4605E+02	1.2604E+02	1.7050E+01	1.3330E+05	3.4316E-07
0.0000	5875.4	2.13316E+01	2.256E+02	2.3692E+03	4.6400E+05	1.4605E+02	1.2604E+02	3.6610E+01	1.2186E+05	3.2486E-07
-0.1000	5696.8	1.49885E+01	2.256E+02	2.3692E+03	4.6400E+05	1.4605E+02	1.2604E+02	5.8242E+01	1.0997E+05	3.0238E-07
-0.2000	5543.1	1.11864E+01	2.256E+02	2.3692E+03	4.6400E+05	1.4605E+02	1.2604E+02	8.1274E+01	9.8263E+04	2.7768E-07
-0.3000	5409.4	8.73575E+00	2.256E+02	2.3692E+03	4.6400E+05	1.4605E+02	1.2604E+02	1.0504E+02	8.7213E+04	2.5255E-07
-0.4000	5295.8	7.06379E+00	2.256E+02	2.3692E+03	4.6400E+05	1.4605E+02	1.2604E+02	1.2903E+02	7.7100E+04	2.2806E-07
-0.5000	5192.1	5.80998E+00	2.256E+02	2.3692E+03	4.6400E+05	1.4605E+02	1.2604E+02	1.5291E+02	6.8018E+04	2.0521E-07
-0.6000	5093.5	4.81886E+00	2.256E+02	2.3692E+03	4.6400E+05	1.4605E+02	1.2604E+02	1.7653E+02	5.9945E+04	1.8436E-07
-0.7000	4994.8	4.00224E+00	2.256E+02	2.3692E+03	4.6400E+05	1.4605E+02	1.2604E+02	1.9975E+02	5.2811E+04	1.6563E-07
-0.8000	4906.1	3.34879E+00	2.256E+02	2.3692E+03	4.6400E+05	1.4605E+02	1.2604E+02	2.2255E+02	4.6524E+04	1.4855E-07
-0.9000	4827.5	2.82042E+00	2.256E+02	2.3692E+03	4.6400E+05	1.4605E+02	1.2604E+02	2.4496E+02	4.0987E+04	1.3300E-07
-1.0000	4758.8	2.39137E+00	2.256E+02	2.3692E+03	4.6400E+05	1.4605E+02	1.2604E+02	2.6702E+02	3.6110E+04	1.1887E-07
-1.1000	4690.1	2.02242E+00	2.256E+02	2.3692E+03	4.6400E+05	1.4605E+02	1.2604E+02	2.8878E+02	3.1812E+04	1.0625E-07
-1.2000	4631.5	1.72307E+00	2.256E+02	2.3692E+03	4.6400E+05	1.4605E+02	1.2604E+02	3.1028E+02	2.8020E+04	9.4772E-08
-1.3000	4582.8	1.48063E+00	2.256E+02	2.3692E+03	4.6400E+05	1.4605E+02	1.2604E+02	3.3157E+02	2.4673E+04	8.4341E-08
-1.4000	4539.1	1.27741E+00	2.256E+02	2.3692E+03	4.6400E+05	1.4605E+02	1.2604E+02	3.5269E+02	2.1721E+04	7.4964E-08
-1.5000	4495.5	1.10053E+00	2.256E+02	2.3692E+03	4.6400E+05	1.4605E+02	1.2604E+02	3.7366E+02	1.9116E+04	6.6613E-08
-1.6000	4456.8	9.52386E-01	2.256E+02	2.3692E+03	4.6400E+05	1.4605E+02	1.2604E+02	3.9451E+02	1.6816E+04	5.9107E-08
-1.7000	4428.2	8.33382E-01	2.256E+02	2.3692E+03	4.6400E+05	1.4605E+02	1.2604E+02	4.1526E+02	1.4788E+04	5.2313E-08
-1.8000	4409.5	7.37876E-01	2.256E+02	2.3692E+03	4.6400E+05	1.4605E+02	1.2604E+02	4.3592E+02	1.3002E+04	4.6192E-08
-1.9000	4390.8	6.53162E-01	2.256E+02	2.3692E+03	4.6400E+05	1.4605E+02	1.2604E+02	4.5649E+02	1.1432E+04	4.0787E-08
-2.0000	4372.2	5.78038E-01	2.256E+02	2.3692E+03	4.6400E+05	1.4605E+02	1.2604E+02	4.7698E+02	1.0052E+04	3.6016E-08
-2.1000	4353.5	5.11436E-01	2.256E+02	2.3692E+03	4.6400E+05	1.4605E+02	1.2604E+02	4.9737E+02	8.8384E+03	3.1803E-08

--:-- guess_1.mod (Text Fill)--L1--C0--Top

Loading mwheel...done

read_model.pro

write_model.pro

modelador3.x

Basilio Ruiz Cobo

Running SIR: input files

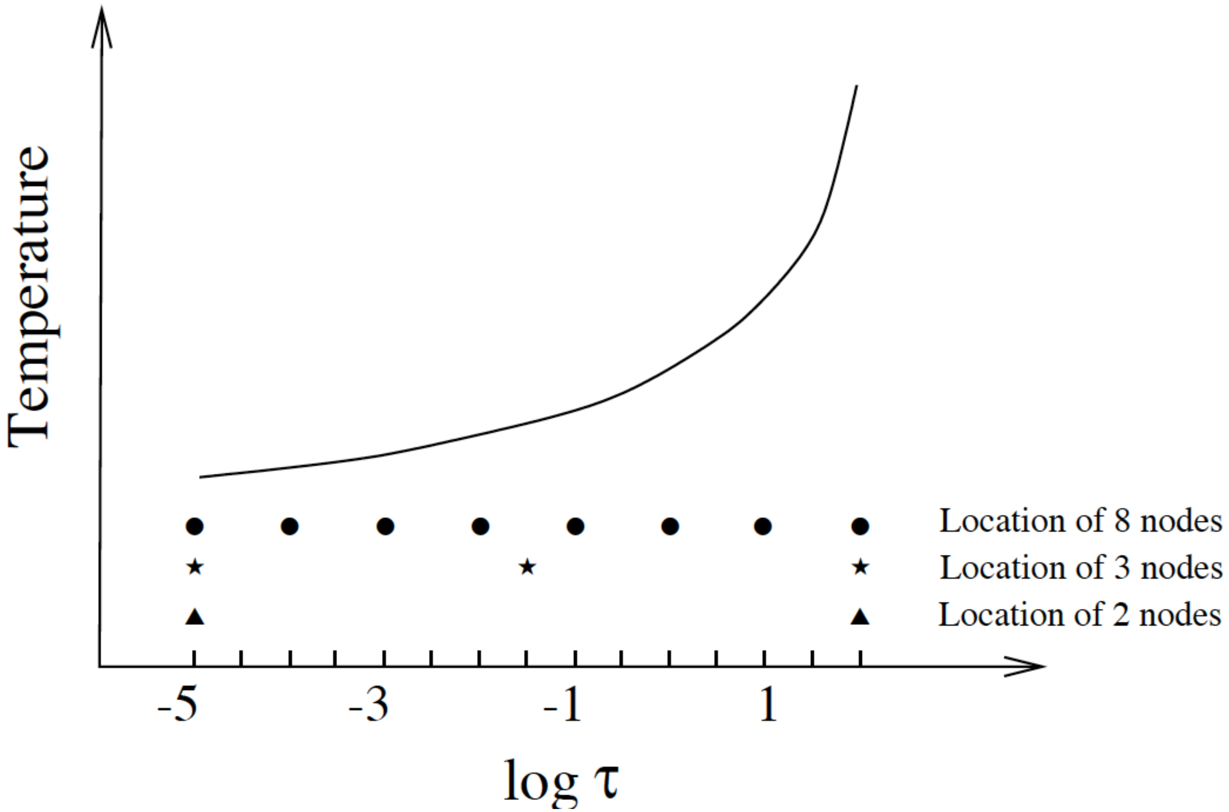
emacs@orion.iaa.es

File Edit Options Buffers Tools Help

```
Number of cycles          (*):1          ! (0=synthesis)
Observed profiles         (*):perfil.per !
Stray light file             :           ! (none=no stray light contam)
PSF file                     :           ! (none=no convolution with PSF)
Wavelength grid file      (s):malla.grid ! (none=automatic selection)
Atomic parameters file       :LINES      ! (none=DEFAULT LINES file)
Abundances file              :THEVENIN   ! (none=DEFAULT ABUNDANCES file)
Initial guess model 1     (*):guess.mod  !
Initial guess model 2        :
Weight for Stokes I          :1          ! (DEFAULT=1; 0=not inverted)
Weight for Stokes Q          :4          ! (DEFAULT=1; 0=not inverted)
Weight for Stokes U          :4          ! (DEFAULT=1; 0=not inverted)
Weight for Stokes V          :4          ! (DEFAULT=1; 0=not inverted)
AUTOMATIC SELECT. OF NODES?  :0          ! (DEFAULT=0=no; 1=yes)
Nodes for temperature 1      :2
Nodes for electr. press. 1   :
Nodes for microturb. 1       :1
Nodes for magnetic field 1   :1
Nodes for LOS velocity 1     :1
Nodes for gamma 1            :1
Nodes for phi 1              :1
Invert macroturbulence 1?    :1          ! (0 or blank=no, 1=yes)
Nodes for temperature 2      :
Nodes for electr. press. 2   :
Nodes for microturb. 2       :
Nodes for magnetic field 2   :
Nodes for LOS velocity 2     :
Nodes for gamma 2            :
Nodes for phi 2              :
Invert macroturbulence 2?    :           ! (0 or blank=no, 1=yes)
Invert filling factor?       :           ! (0 or blank=no, 1=yes)
Invert stray light factor?   :           ! (0 or blank=no, 1=yes)
mu=cos (theta)               :0.64       ! (DEFAULT: mu=1. mu<0 => West)
Estimated S/N for I          :200        ! (DEFAULT: 1000)
Continuum contrast           :           ! (DEFAULT: not used)
Tolerance for SVD            :           ! (DEFAULT value: 1e-4)
Initial diagonal element     :           ! (DEFAULT value: 1.e-3)
Splines/Linear Interpolation :           ! (0 or blank=splines, 1=linear)
Gas pressure at surface 1    :           ! (0 or blank=Pe boundary cond.)
Gas pressure at surface 2    :           ! (0 or blank=Pe boundary cond.)
Magnetic pressure term?      :0          ! (0 or blank=no, 1=yes)
NLTE Departures filename     :           ! blanck= LTE (Ej. depart_6494.dat'
--:**  sir.trol        (Text Fill)--L1--C0--Top---------------------------------
```

Concept of nodes

- Keeping the number of free parameters small:
  - Atmospheric parameters perturbed in coarse grid (nodes)
  - Full stratifications in finer grid by cubic spline interpolation



Running SIR: input files

```
emacs@orion.iaa.es
File  Edit  Options  Buffers  Tools  Help

Number of cycles            (*):1           ! (0=synthesis)
Observed profiles           (*):perfil.per  !
Stray light file               :            ! (none=no stray light contam)
PSF file                       :            ! (none=no convolution with PSF)
Wavelength grid file        (s):malla.grid  ! (none=automatic selection)
Atomic parameters file         :LINES       ! (none=DEFAULT LINES file)
Abundances file                :THEVENIN    ! (none=DEFAULT ABUNDANCES file)
Initial guess model 1       (*):guess.mod   !
Initial guess model 2          :
Weight for Stokes I            :1           ! (DEFAULT=1; 0=not inverted)
Weight for Stokes Q            :4           ! (DEFAULT=1; 0=not inverted)
Weight for Stokes U            :4           ! (DEFAULT=1; 0=not inverted)
Weight for Stokes V            :4           ! (DEFAULT=1; 0=not inverted)
AUTOMATIC SELECT. OF NODES?    :0           ! (DEFAULT=0=no; 1=yes)
Nodes for temperature 1        :2
Nodes for electr. press. 1     :
Nodes for microturb. 1         :1
Nodes for magnetic field 1     :1
Nodes for LOS velocity 1       :1
Nodes for gamma 1              :1
Nodes for phi 1                :1
Invert macroturbulence 1?      :1           ! (0 or blank=no, 1=yes)
Nodes for temperature 2        :
Nodes for electr. press. 2     :
Nodes for microturb. 2         :
Nodes for magnetic field 2     :
Nodes for LOS velocity 2       :
Nodes for gamma 2              :
Nodes for phi 2                :
Invert macroturbulence 2?      :            ! (0 or blank=no, 1=yes)
Invert filling factor?         :            ! (0 or blank=no, 1=yes)
Invert stray light factor?     :            ! (0 or blank=no, 1=yes)
mu=cos (theta)                 :0.64        ! (DEFAULT: mu=1. mu<0 => West)
Estimated S/N for I            :200         ! (DEFAULT: 1000)
Continuum contrast             :            ! (DEFAULT: not used)
Tolerance for SVD              :            ! (DEFAULT value: 1e-4)
Initial diagonal element       :            ! (DEFAULT value: 1.e-3)
Splines/Linear Interpolation   :            ! (0 or blank=splines, 1=linear)
Gas pressure at surface 1      :            ! (0 or blank=Pe boundary cond.)
Gas pressure at surface 2      :            ! (0 or blank=Pe boundary cond.)
Magnetic pressure term?        :0           ! (0 or blank=no, 1=yes)
NLTE Departures filename       :            ! blanck= LTE (Ej. depart_6494.dat'

--:**  sir.trol        (Text Fill)--L1--C0--Top-----------------------------
```

Number of nodes selection:

- For each cycle it reads the corresponding column, so if, we have 2 cycles and
  Nodes for T: 2,3
  Nodes for B: 1
  In the first cycle it takes 2 for T and 1 for B
  In the second: 3 for T and 1 for B
- If nodes for elec. Pressure 0= HE
- If nodes = -1 it evaluates the perturbation for the other atmosphere
- If “Authomatic selection of nodes” is for instance 0,1 it means that for the first cycle it uses the number of nodes specified, but for the second it takes a number lower that the specified
- Number of nodes * means any value (only for authomatic selection)

Running SIR: input files

emacs@orion.iaa.es

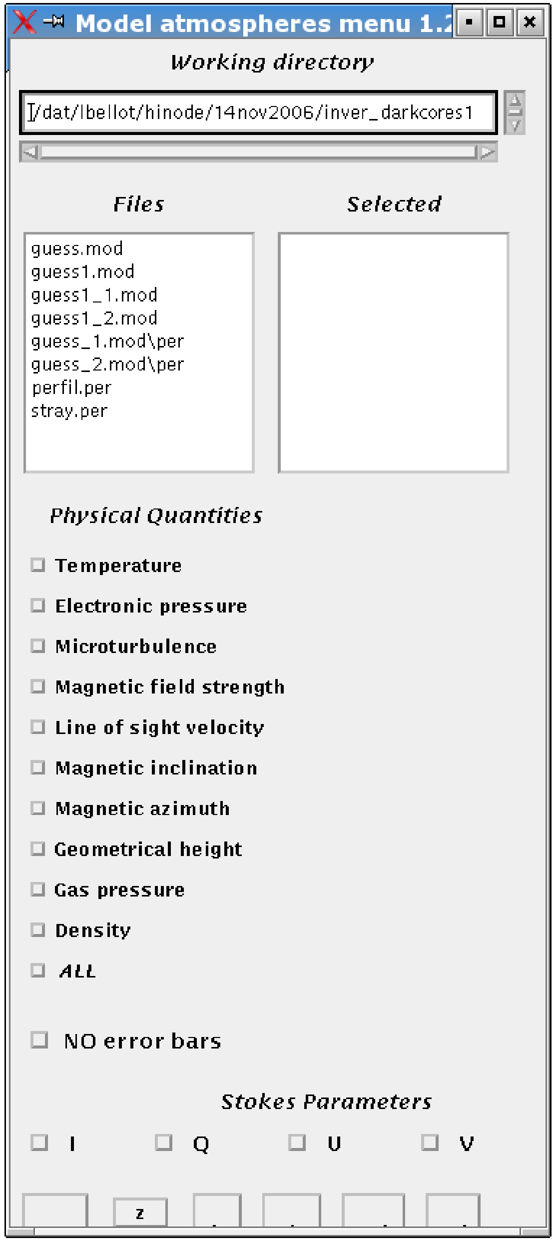
File Edit Options Buffers Tools Help

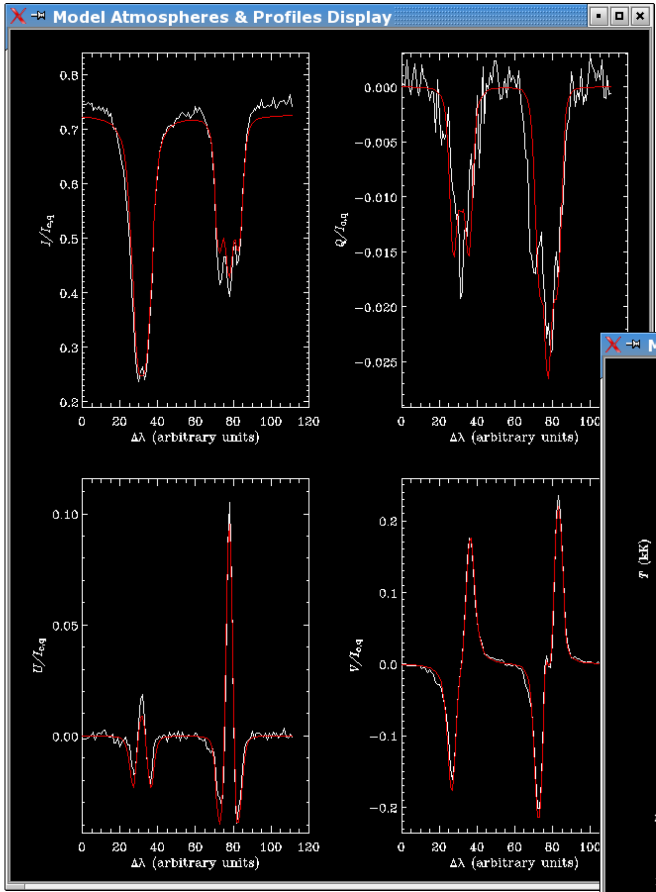
```
Number of cycles          (*):1          ! (0=synthesis)
Observed profiles         (*):perfil.per !
Stray light file             :           ! (none=no stray light contam)
PSF file                     :           ! (none=no convolution with PSF)
Wavelength grid file      (s):malla.grid ! (none=automatic selection)
Atomic parameters file       :LINES      ! (none=DEFAULT LINES file)
Abundances file              :THEVENIN   ! (none=DEFAULT ABUNDANCES file)
Initial guess model 1     (*):guess.mod  !
Initial guess model 2        :
Weight for Stokes I          :1          ! (DEFAULT=1; 0=not inverted)
Weight for Stokes Q          :4          ! (DEFAULT=1; 0=not inverted)
Weight for Stokes U          :4          ! (DEFAULT=1; 0=not inverted)
Weight for Stokes V          :4          ! (DEFAULT=1; 0=not inverted)
AUTOMATIC SELECT. OF NODES?  :0          ! (DEFAULT=0=no; 1=yes)
Nodes for temperature 1      :2
Nodes for electr. press. 1   :
Nodes for microturb. 1       :1
Nodes for magnetic field 1   :1
Nodes for LOS velocity 1     :1
Nodes for gamma 1            :1
Nodes for phi 1              :1
Invert macroturbulence 1?    :1          ! (0 or blank=no, 1=yes)
Nodes for temperature 2      :
Nodes for electr. press. 2   :
Nodes for microturb. 2       :
Nodes for magnetic field 2   :
Nodes for LOS velocity 2     :
Nodes for gamma 2            :
Nodes for phi 2              :
Invert macroturbulence 2?    :           ! (0 or blank=no, 1=yes)
Invert filling factor?       :           ! (0 or blank=no, 1=yes)
Invert stray light factor?   :           ! (0 or blank=no, 1=yes)
mu=cos (theta)               :0.64       ! (DEFAULT: mu=1. mu<0 => West)
Estimated S/N for I          :200        ! (DEFAULT: 1000)
Continuum contrast           :           ! (DEFAULT: not used)
Tolerance for SVD            :           ! (DEFAULT value: 1e-4)
Initial diagonal element     :           ! (DEFAULT value: 1.e-3)
Splines/Linear Interpolation :           ! (0 or blank=splines, 1=linear)
Gas pressure at surface 1    :           ! (0 or blank=Pe boundary cond.)
Gas pressure at surface 2    :           ! (0 or blank=Pe boundary cond.)
Magnetic pressure term?      :0          ! (0 or blank=no, 1=yes)
NLTE Departures filename     :           ! blanck= LTE (Ej. depart_6494.dat'

--:**  sir.trol        (Text Fill)--L1--C0--Top-----------------------------------
```

Executing the inversion

```
echo sir.trol | sir.x
```

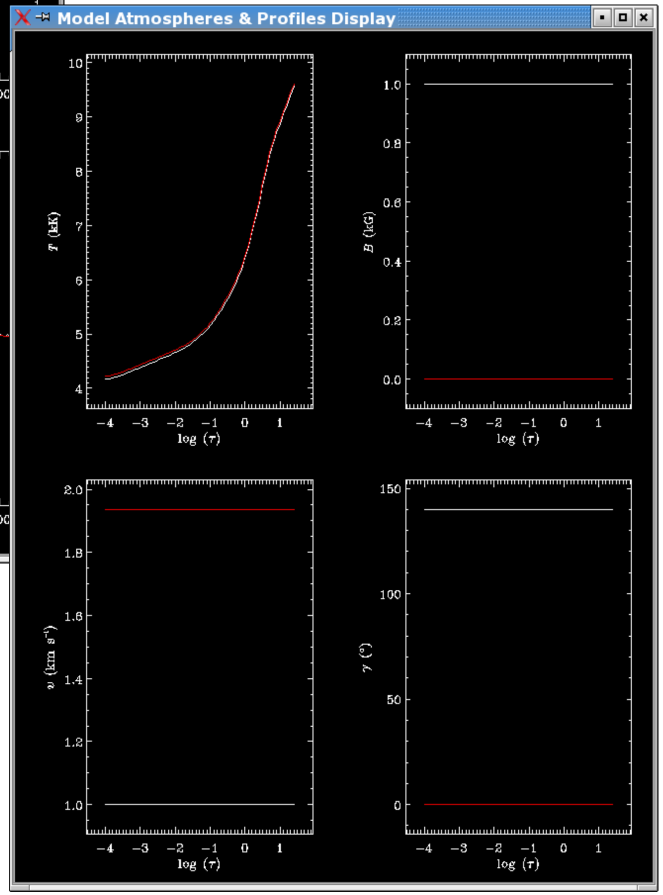
Visualizing SIR results: graphics2.pro





Stokes profiles

Model atmospheres



Basilio Ruiz Cobo

SIR Exercises

Download exercises from:

https://github.com/BasilioRuiz/SIR-course

Exercise 1

Spectral synthesis and inversion of synthetic profiles

- Use HSRA model to synthesize Stokes profiles with
  1. constant B, inclination and v_{LOS} (e.g., 1 kG, 60º, 2 km/s)
  2. constant v_{LOS}, gradients of B and inclination
  3. gradients of B, inclination and v_{LOS}

- Invert profiles from (3.), starting from initial guess model with flat stratifications of B, v_{LOS} , and inclination (modify hsra11.mod)
  - 1 node in B, v_{LOS}, inclination
  - 2 nodes in B, and v_{LOS} inclination

```
IDL> read_model,'hsra11.mod',logtau,T,pe,mic,B,V_LOS,gamma,phi,mac,filling,stray
IDL> B=1000+400.*logtau          &   v=2.e5+0.*logtau       & gamma=60.+  0.*logtau

IDL> write_model,'model1.mod',logtau,T,pe,mic,B,V_LOS,gamma,phi,mac,filling,stray
```

Exercise 2

Inversion of profiles from dark-cored penumbral filament.

• Hinode/SO observations with SNR~1000, no telluric lines, 2 lines Fe I 630.1 & 630.2 nm. Strong, symmetric signals.

1. What kind of model would you use to invert them?
2. Can the fit be improved with more nodes in T? (use 2 cycles!)
3. What happens with 2 nodes in B and v_{LOS}?
4. What happens with 10 nodes in B and v_{LOS}?

• Invert profiles from (3.), starting from initial guess model with flat stratifications of B, v_{LOS}, and inclination (modify hsra.mod)

   1. One node in B, v_{LOS}, inclination.
   2. Two nodes in B, v_{LOS}, inclination.

If no instrumental PSF is available, use macroturbulence to mimic its effect (i.e, invert v_{mac})

Use more weight for Q, U and V to force better fits to those parameters

Exercise 3

Error estimation and Region of sensitivity.

- Evaluate the error bars for magnetic field strength, inclination and azimuth for the last inversion of Exercise 2

- Evaluate the region of sensitivity of the azimuth.

SIR writes the error bars in a .err file that you can read using:

IDL> read_model,' [   ].err',logtau,T_err,p_err,mic_err,B_err,V_LOS,gamma,phi,mac,filling,stray

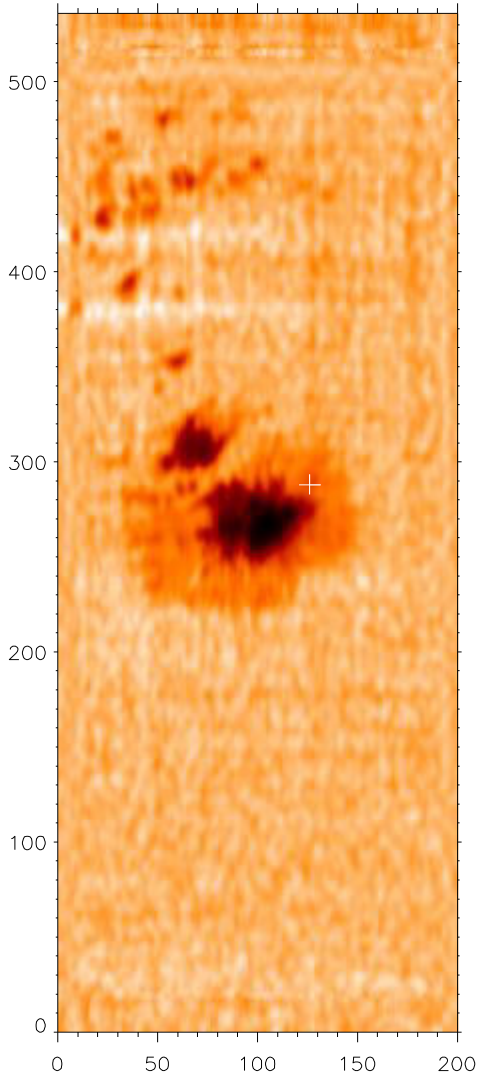
And the region of sensitivity by:

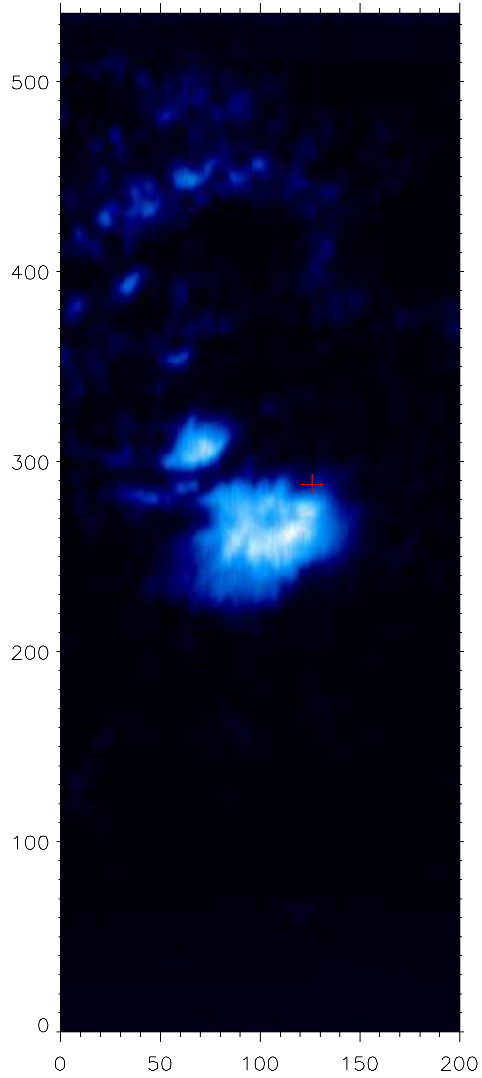
IDL> sensitivity, Stokes_obs,Stokes_syn,model,RF,logtau,uncertainties

Exercise 4

Inversion of SPINOR data

SPINOR: Spectro Polarimeter for Infrared and Optical Regions (NSO/HAO)
@ Dunn Solar Telescope on Sacramento Peak

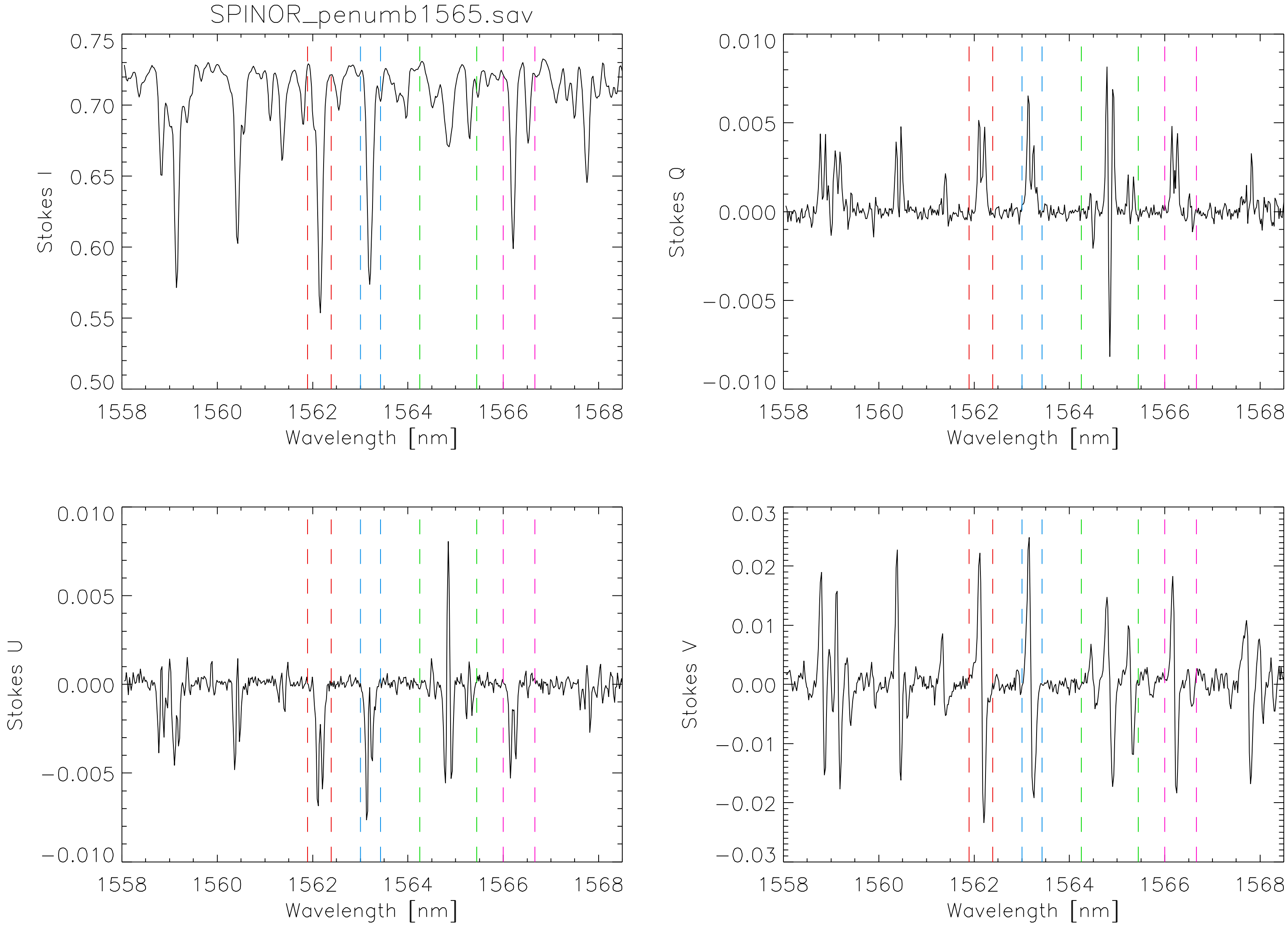




Exercise 4

Inversion of SPINOR data

SPINOR: Spectro Polarimeter for Infrared and Optical Regions (NSO/HAO) @ Dunn Solar Telescope on Sacramento Peak



Exercise 4

Inversion of SPINOR data

SPINOR: Spectro Polarimeter for Infrared and Optical Regions (NSO/HAO)
@ Dunn Solar Telescope on Sacramento Peak

Multiline inversion including blends

1. Select the spectral regions around the Fe I lines:
   1562.1, 1563.2, 1564.5 (blended with 64.85 & 65.29), 1566.2 (blended with 66.5)
2. Write the profile and grid files
3. Invert, including micro- and macro-turbulence (because we have not used PSF). Use 2 cycles to obtain gradients (because we have several lines), increasing number of nodes in 2nd cycle.

Exercise 4 bis

Inversion of facular profiles in quiet Sun.

Advanced Stokes Polarimeter (HAO) observations, averaged over facular region, SNR~10000, but poor spatial resolution.
Two lines Fe I 630.1 and 630.2 nm (plus telluric lines!) .
Strong signals, large Stokes V area and amplitude asymmetries.

1. What kind of model would you use to invert them?
2. Use two cycles, increasing number of nodes in 2nd cycle.
3. Invert stray-light fraction, micro- and macro-turbulence.

We invert Stokes I and V only, so vertical fields should be assumed.
Use large negative number (e.g., -2) in profiles to ignore blends in Stokes I during inversion .
Use instrumental PSF and macroturbulence at the same time.
Use stray light profile.
Use weights of 10 and 100 for Stokes V.

Exercise 5

Inversion of quiet-Sun internetwork.

Hinode/SP observations at disk center, integrated for 6 min, SNR~10^5, still high spatial resolution.
Two lines Fe I 630.1 and 630.2 nm
Extremely weak signals, but linear polarization clearly seen.
Large asymmetries.

1. What kind of model would you use to invert them?
2. Use three cycles with increasing number of nodes.
3. Invert stray-light fraction, microturbulence (flat stratification).
4. Interpret resulting model .

No need for macroturbulence when high-resolution data are inverted using telescope PSF
Use following weights: 1,4,4,4

Exercise 6

Inversion of sunspot penumbral profiles near PIL

Hinode/SP observations with SNR~1000, no telluric lines, two lines Fe I 630.1 and 630.2 nm.

Strong signals, but Stokes V profile with three lobes...

1. What kind of model would you use to invert them?
2. One-component model with opposite magnetic along LOS? Two-component model?
3. Try both!

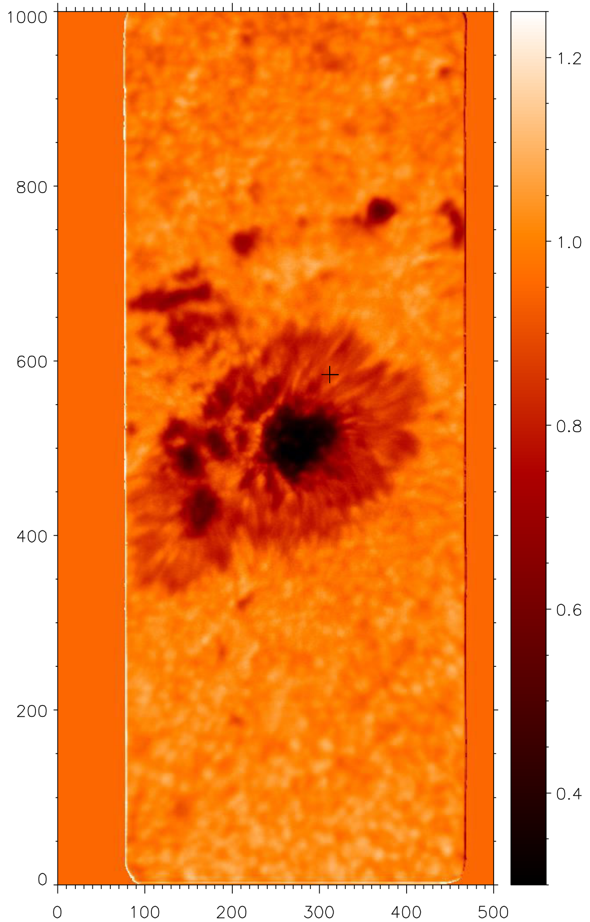
Inversion of these profiles will not be easy. Do your best!
Give more weight to Stokes V to force better fits. Increase weight with cycle.
Use instrumental PSF and macroturbulence at the same time.
If everything fails, use superpowers....

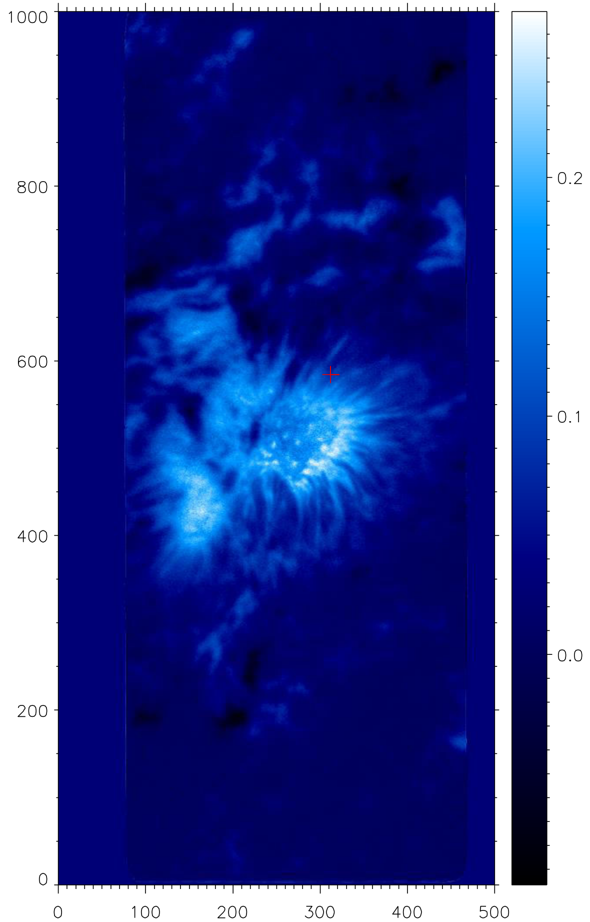
Exercise 7

Inversion of IBIS profiles

IBIS: Interferometric Bidimensional Spectropolarimeter (INAF_Arcetri OBS/NSO)
@ Dunn Solar Telescope on Sacramento Peak

Penumbra observed at Fe I 6173 A

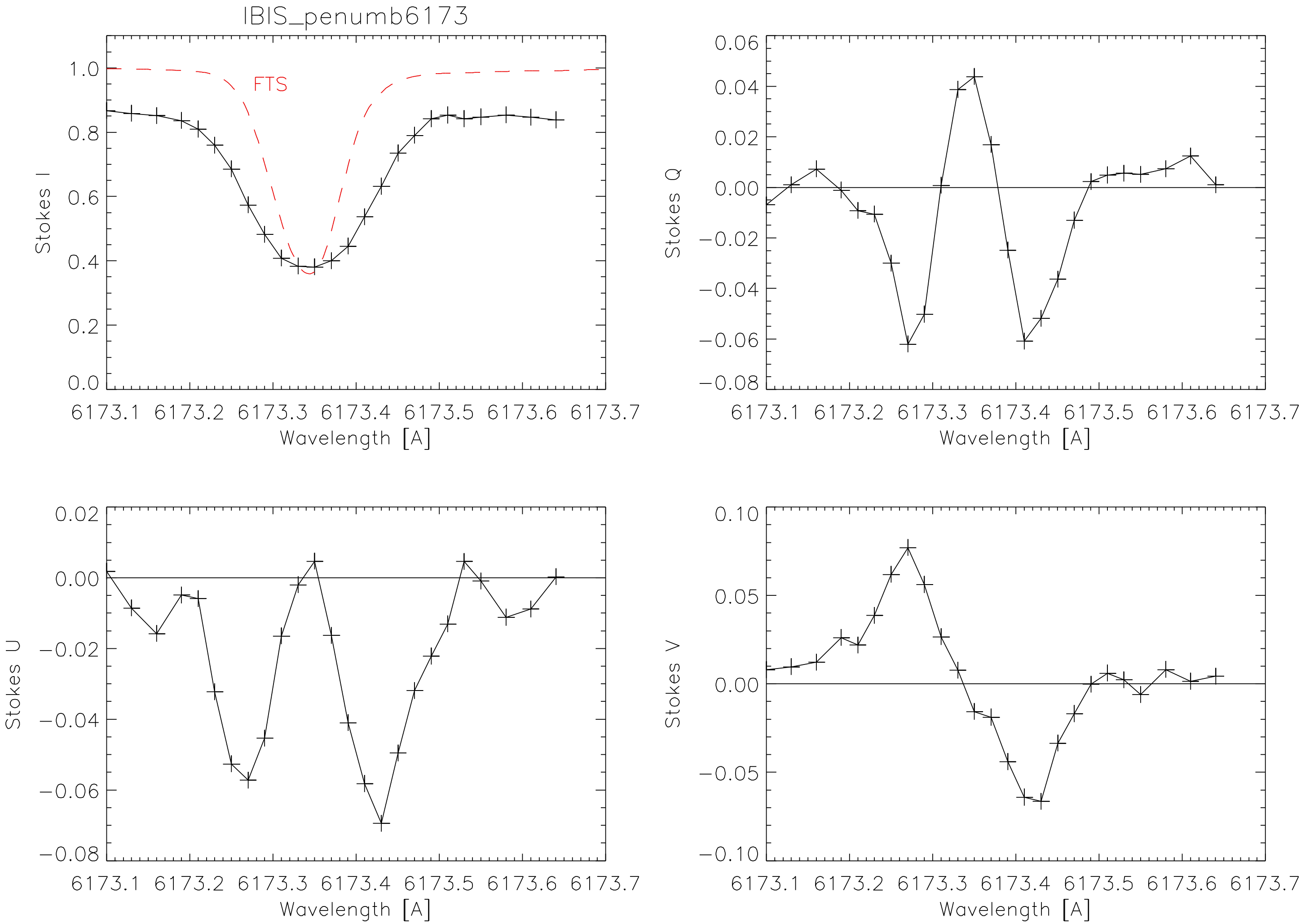




Exercise 7

Inversion of IBIS profiles

IBIS: Interferometric Bidimensional Spectropolarimeter (INAF_Arcetri OBS/NSO)
@ Dunn Solar Telescope on Sacramento Peak



Exercise 7

Inversion of IBIS profiles

IBIS: Interferometric Bidimensional Spectropolarimeter (INAF_Arcetri OBS/NSO)
@ Dunn Solar Telescope on Sacramento Peak

High spatial resolution

1. Profiles are not equally spaced in wavelength: interpolate to a 10 mA resolution and write a “-1” over the new points
2. The profiles are wider than FTS, then, as we have not the PSF, we should include a macroturbulence.

Example of Stokes profiles observed with a Fabry-Pérot interferometer.
High spatial resolution, but modest spectral resolution (20-30 mA at 617 nm).
To include points in the profile you can use:
IDL> introduce_points,x,si,sq,su,sv, x1,si1, sq1,su1,sv1
Where x is the old grid and x1 the new one

Exercise 7bis

Inversion of CRISP profiles from sunspot penumbrae

SST/CRISP observations with SNR~500, sequential spectral sampling of Fe I 617.3 nm (30 wavelengths in ~30 s)
Strongly Doppler-shifted polarization profiles

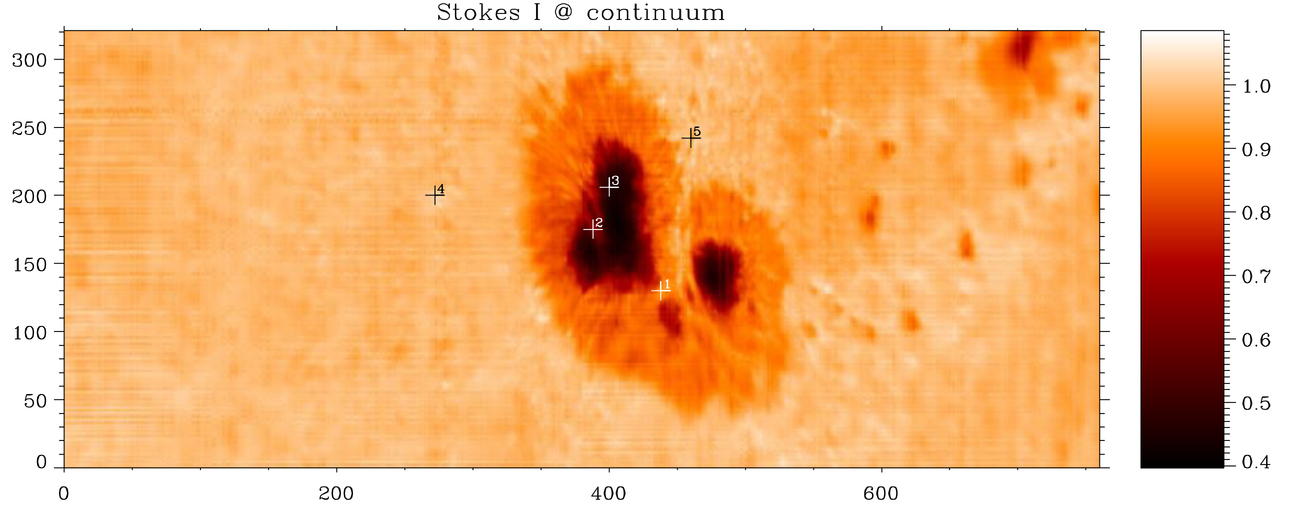
1. What kind of model would you use to invert them?
2. Include stray-light contamination, and a small weight for Q & U stokes profile (for instance: 10, 0.1,0.1,10)

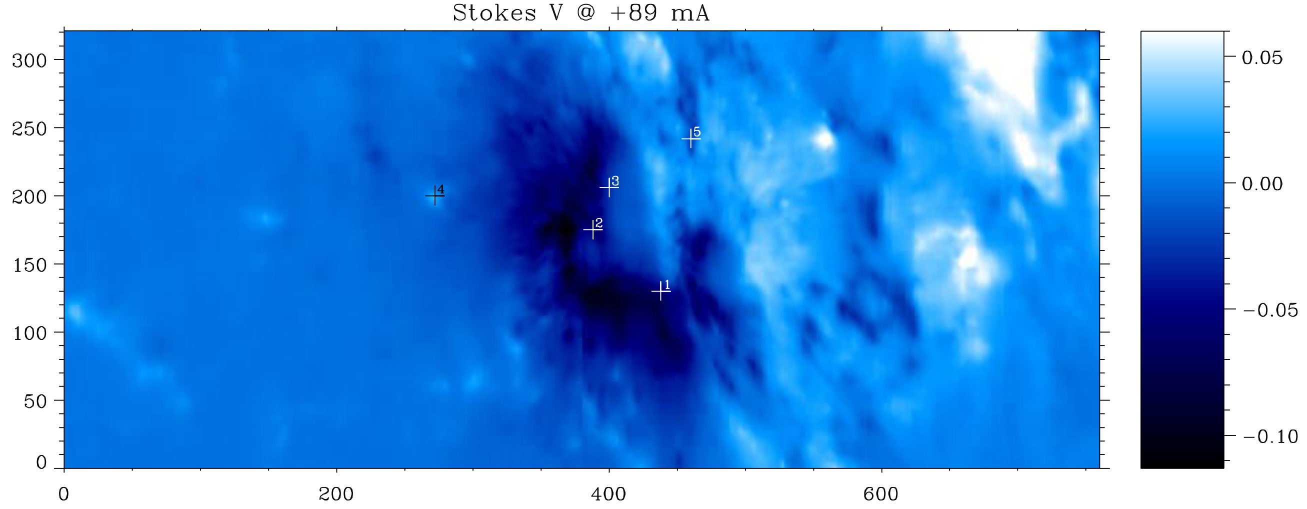
Example of Stokes profiles observed with a Fabry-Pérot interferometer.
Extremely high spatial resolution, but modest spectral resolution (~50 mA at 617 nm).
Sequential sampling of line means first and last wavelengths are observed ~30 s apart.

Exercise 8

Inversion of FIRS profiles

FIRS: Facility Infrared Spectropolarimeter (Univ. Hawai'i/NSO)
@ Dunn Solar Telescope on Sacramento Peak

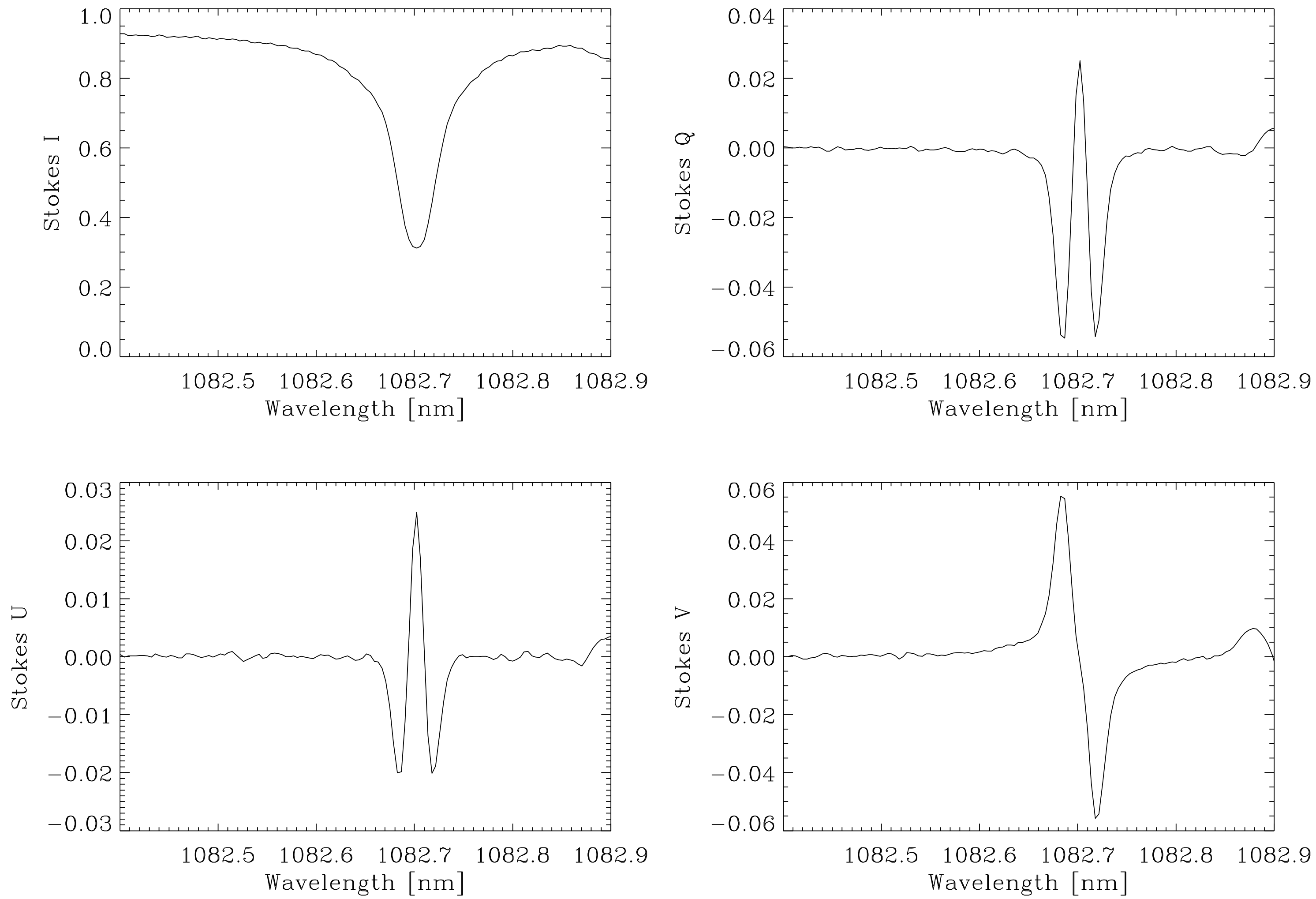




Exercise 8

Inversion of FIRS profiles

FIRS: Facility Infrared Spectropolarimeter (Univ. Hawai'i/NSO)
@ Dunn Solar Telescope on Sacramento Peak



Exercise 8

Inversion of FIRS profiles

FIRS: Facility Infrared Spectropolarimeter (Univ. Hawai'i/NSO)
@ Dunn Solar Telescope on Sacramento Peak

1. Invert the 5 profiles of the pixels marked on the map. Try to determine gradients of B and V_LoS in the second cycle.

2. Are these gradients reliable?

Exercise 9

Inversion of Gas Pressure (simulated data)

We have selected the spectral region 614.7 – 615.1 containig Fe I, Fe II, Ti & V lines, because they show different sensitivity to T & Pg

1) I have perturbed the VALC model introducing a 10% perturbation in T & Pg, and synthetized the profiles. Try to recover T and Pg perturbations by inverting the simulated profiles.

2) I have included a velocity perturbation. Try to recover T, Pg and v_{LOS} perturbations.

3) Determine the region of maximum sensitivity (the logtau range) to relative perturbation of Pg using the Response Functions of T and Pe. Which is the minimum S/N ratio we would need in order to recover a Pg perturbation of around a 10%?

- For the case 2) use several cycles, first inverting T & Pe in Hydrostatic Equilibrium and later allow also for Pe perturbations.
- Evaluate the RF to T & Pe. You can read it using:
  IDL> read_RF_nomag, 'guess_4.rpe' ,rpe ,ntau, nlam
  To evaluate RF to Pg apply the chain rule. You can calculate dPg/dPe and dPg/dT by using
  IDL> Pgderivatives,T,Pe,Pg,dlogPgdT,dlogPgdPe
  This programs calls to the fortran program Pgderivatives_i.x. To compile this program (in the SIR folder):
  make fc=gfortran Pgderivatives_i.x or make Pgderivatives_i.x (if you use the ifort compiler)
  To get the RF to relative perturbation multiply the RF by the parameter.
- Evaluate, for each optical depth, the maximum response (RF at the wavelength at which |RF| is max).