

# The art of Stokes inversions

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# 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:

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

Absorption coefficient:

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

Emission:

$$\eta_\nu$$

Optical depth:

$$d\tau_\nu = -\chi_\nu ds \quad (\text{number of mean free path at } \nu)$$

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

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

# 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:  $d\tau_c = -\chi_c ds$

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

$$S_\nu$$

per cm      per gram

$$\chi_\nu = \kappa_\nu \rho$$

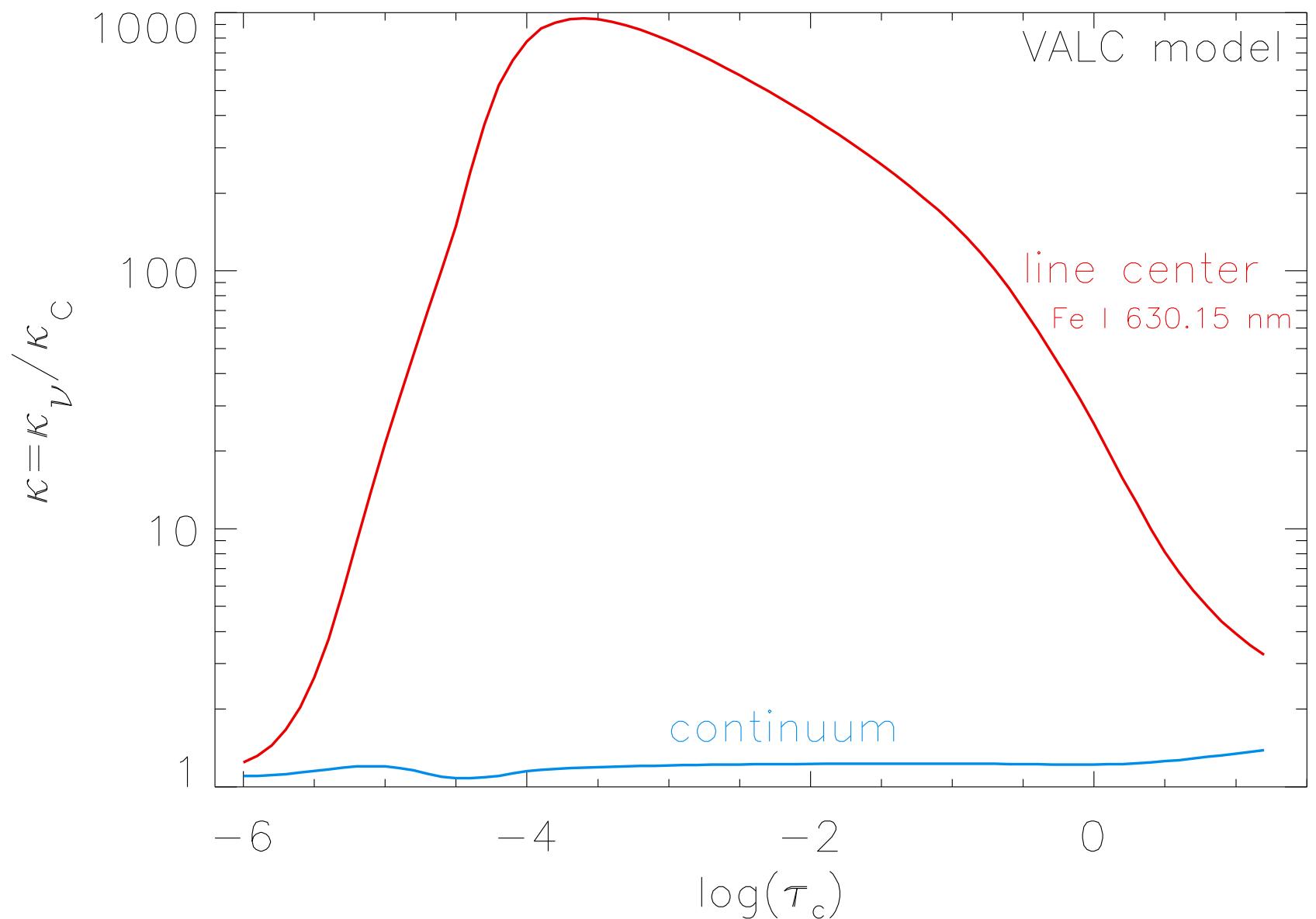
$$\frac{\chi_\nu}{\chi_c} = \frac{\kappa_\nu}{\kappa_c} = \kappa$$

$$\chi_c = \kappa_c \rho$$

$$\frac{\chi_c}{\kappa_c}$$

# 1: The RTE: formal solution & approximations

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



# 1: The RTE: formal solution & approximations

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

Formal solution: integration factor  $O$

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

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

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

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

# 1: The RTE: formal solution & approximations

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

Formal solution: integration factor  $O$

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

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

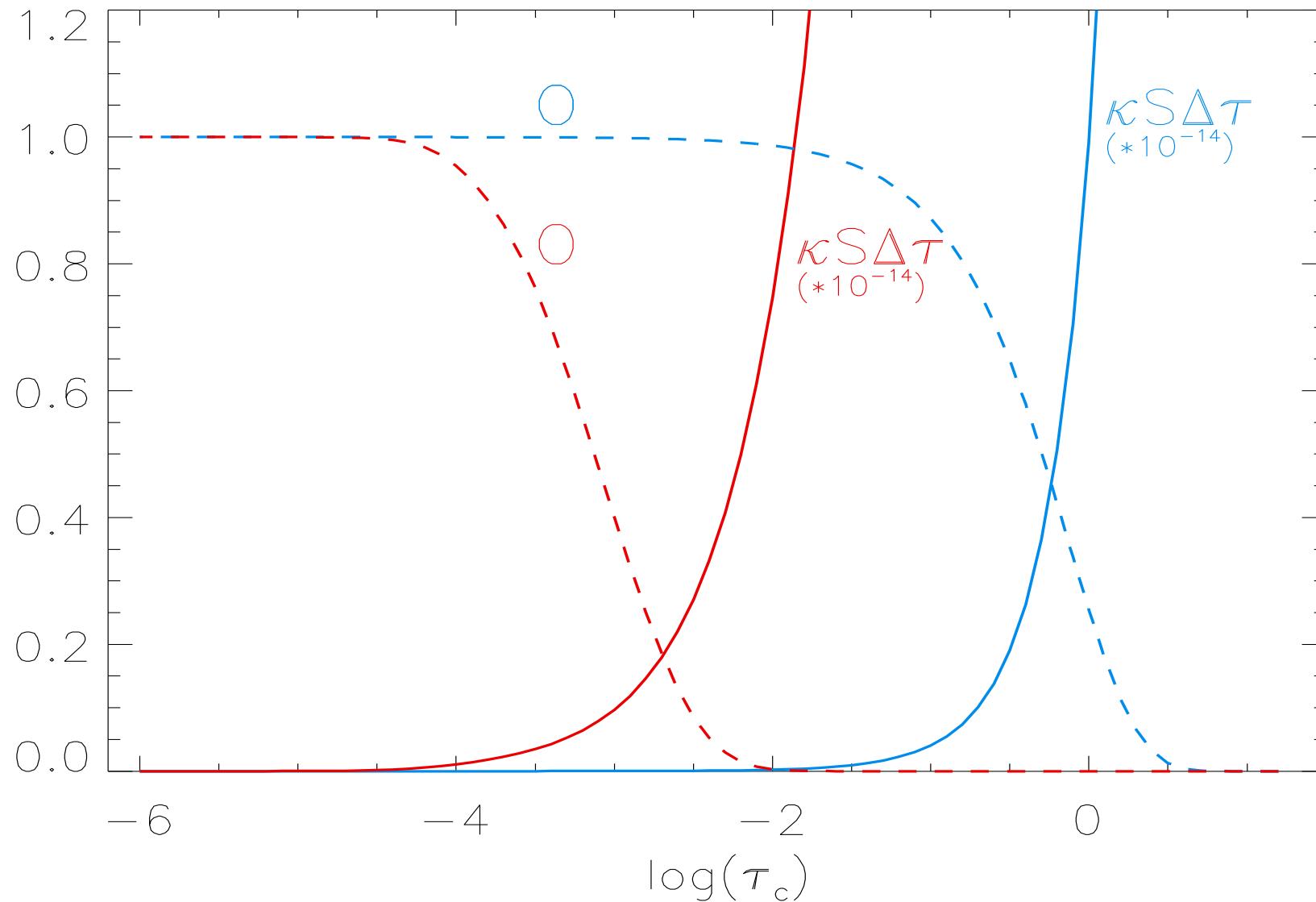
$$O(\tau) = e^{-\int_0^\tau \kappa d\tau}$$

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

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

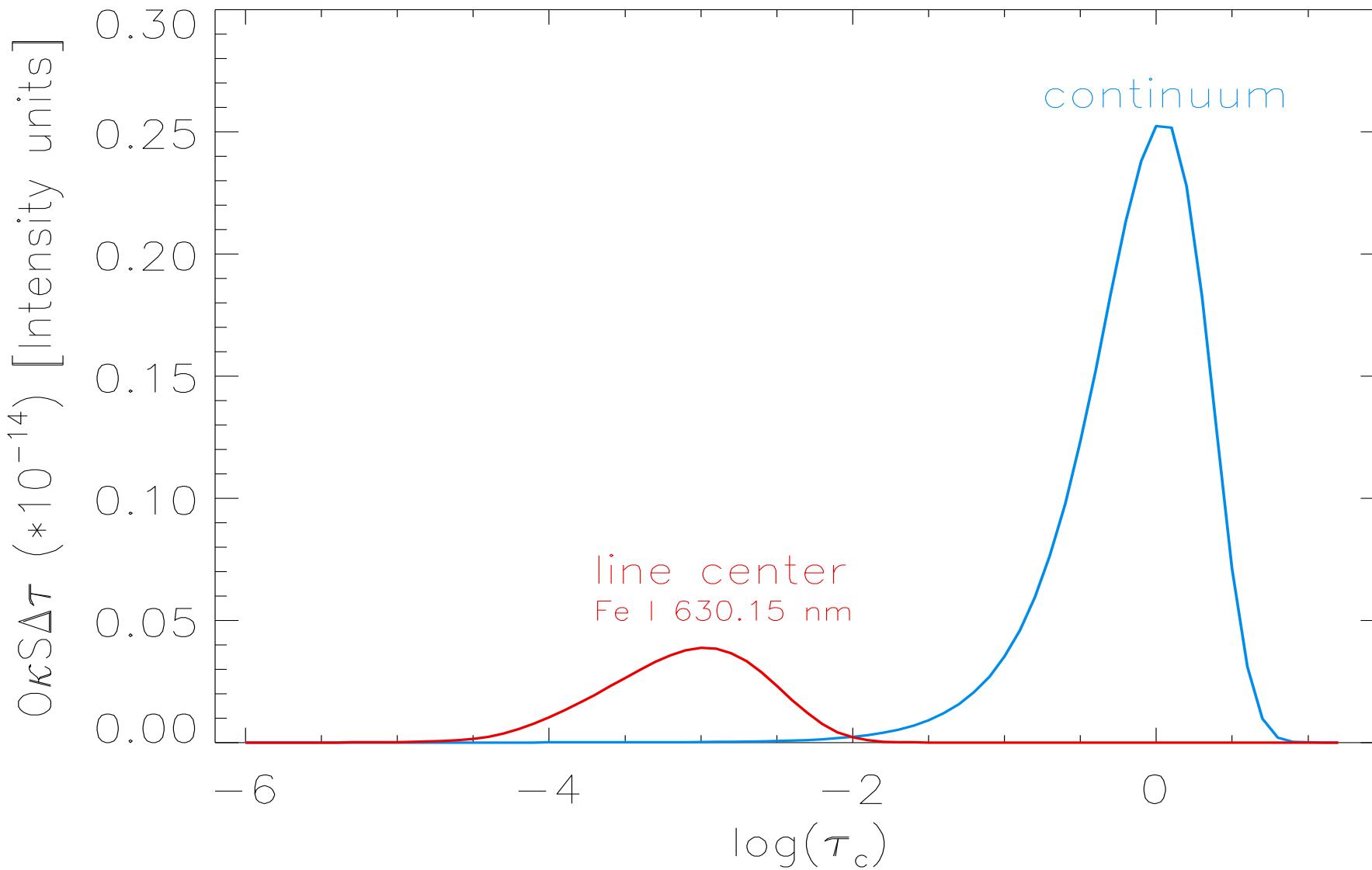
# 1: The RTE: formal solution & approximations

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



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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

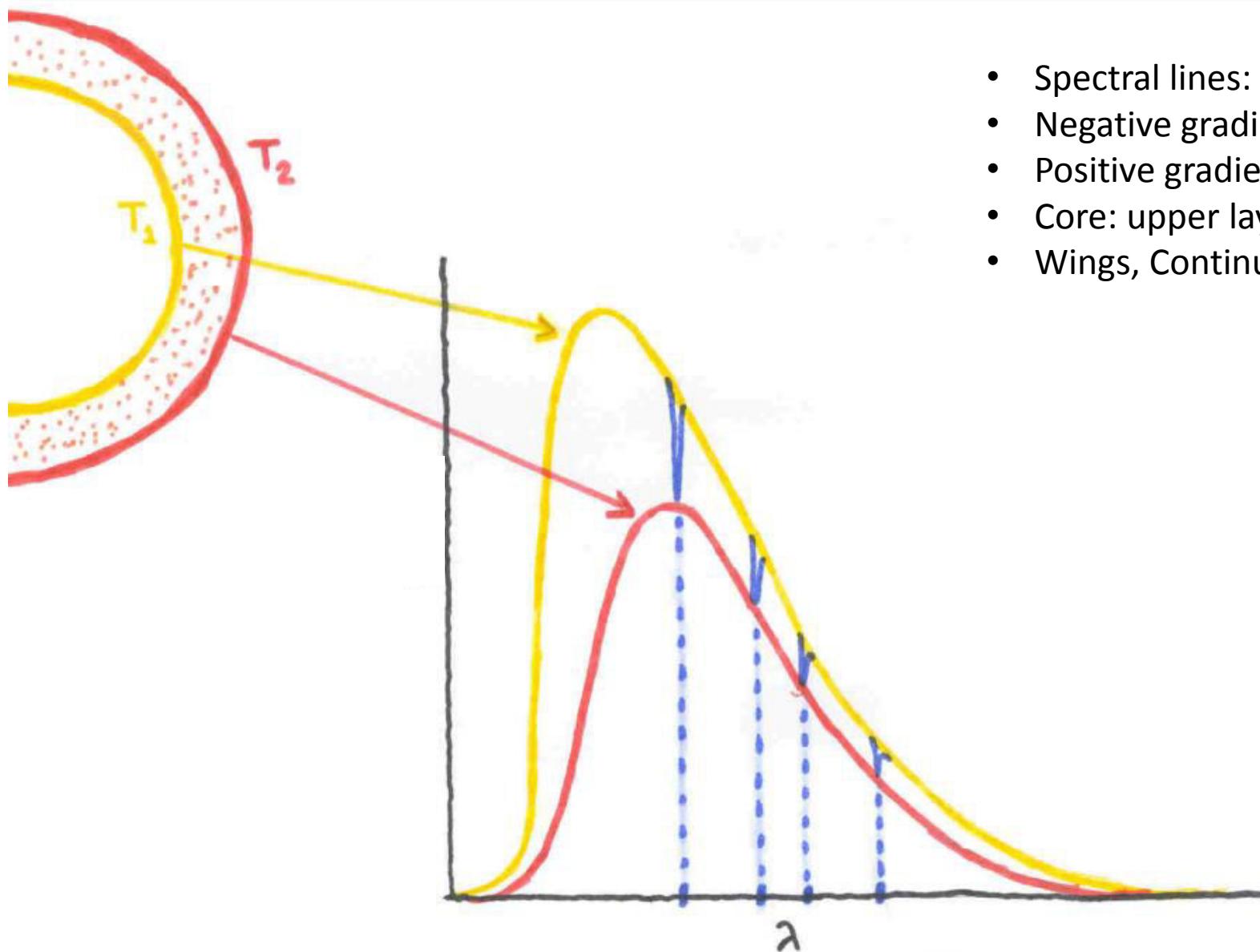
Some possible approximations:

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

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

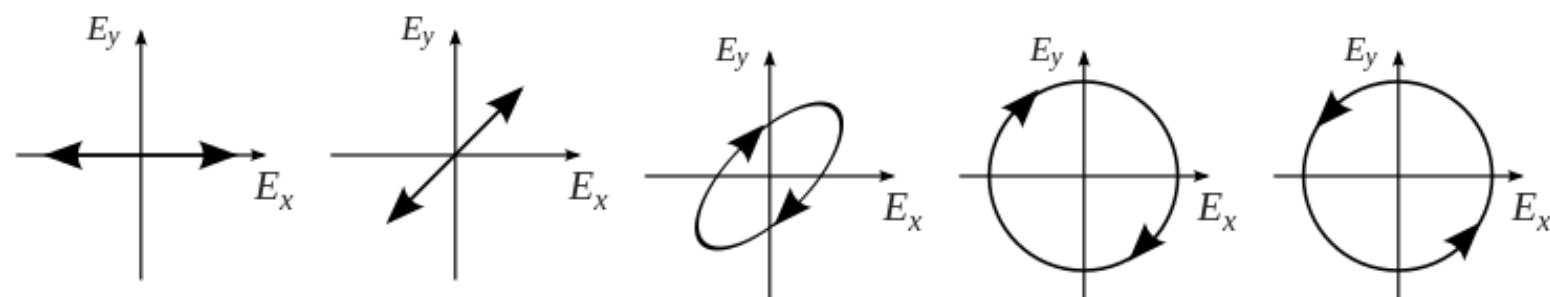
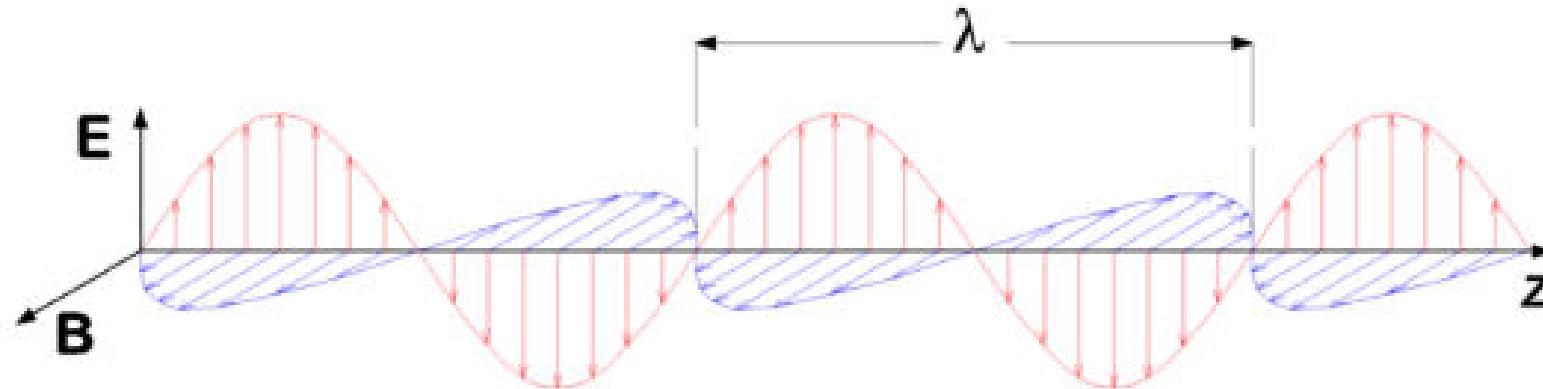
# 1: The RTE: formal solution & approximations

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



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

# 1: The RTE: formal solution & approximations



$$I = \uparrow + \leftrightarrow$$

$$Q = \uparrow - \leftrightarrow$$

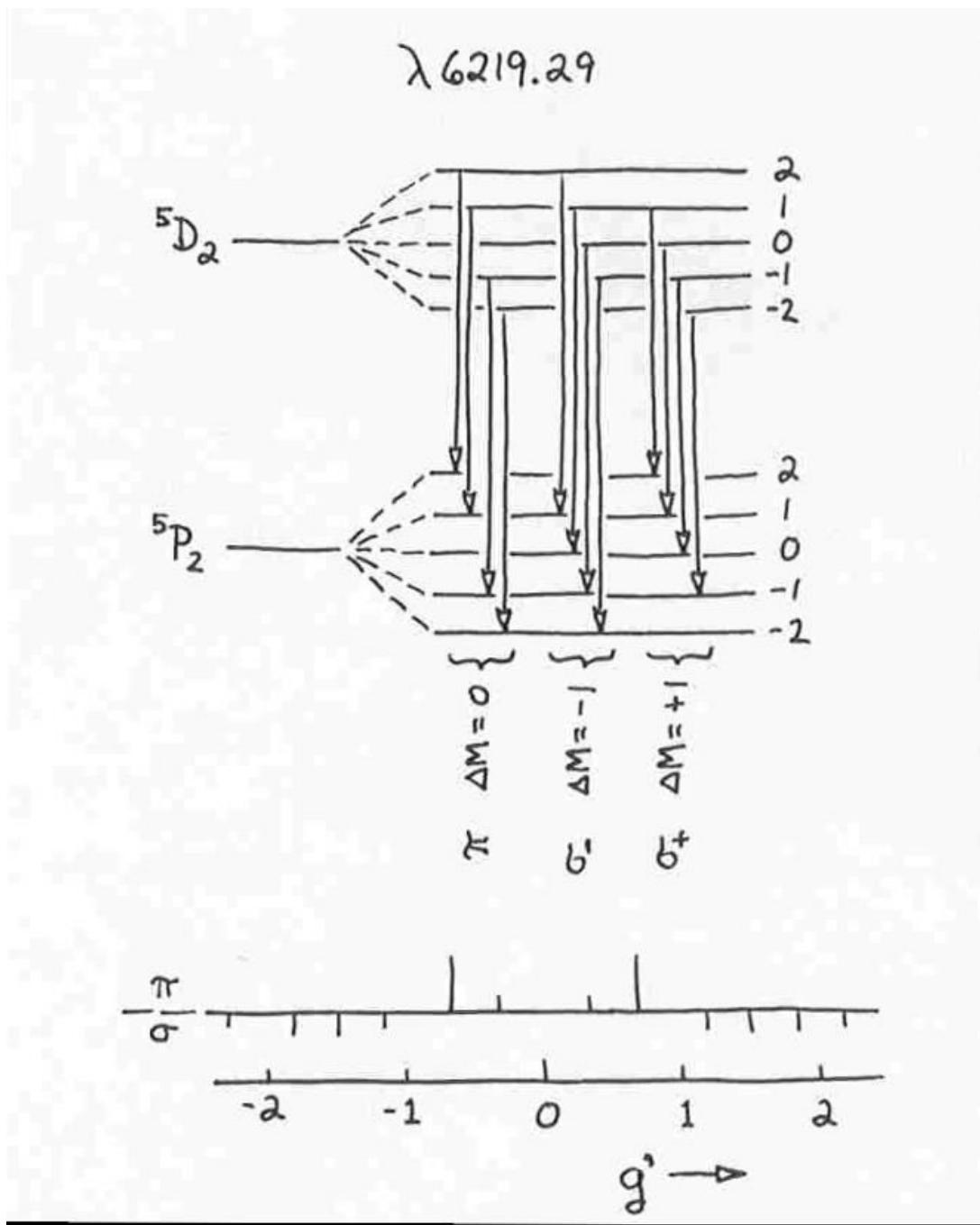
$$U = \nearrow - \nwarrow$$

$$V = \circlearrowleft - \circlearrowright$$

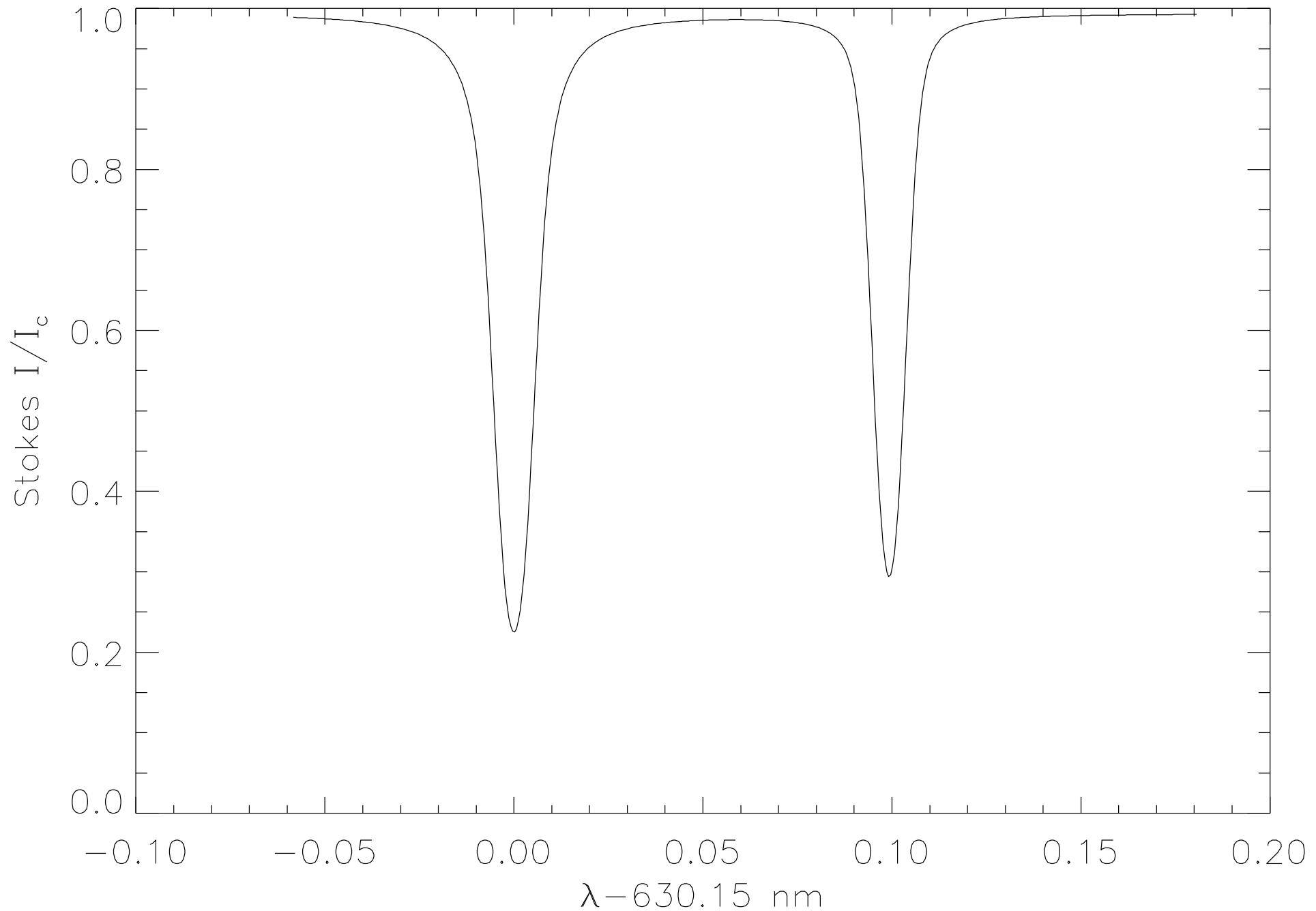
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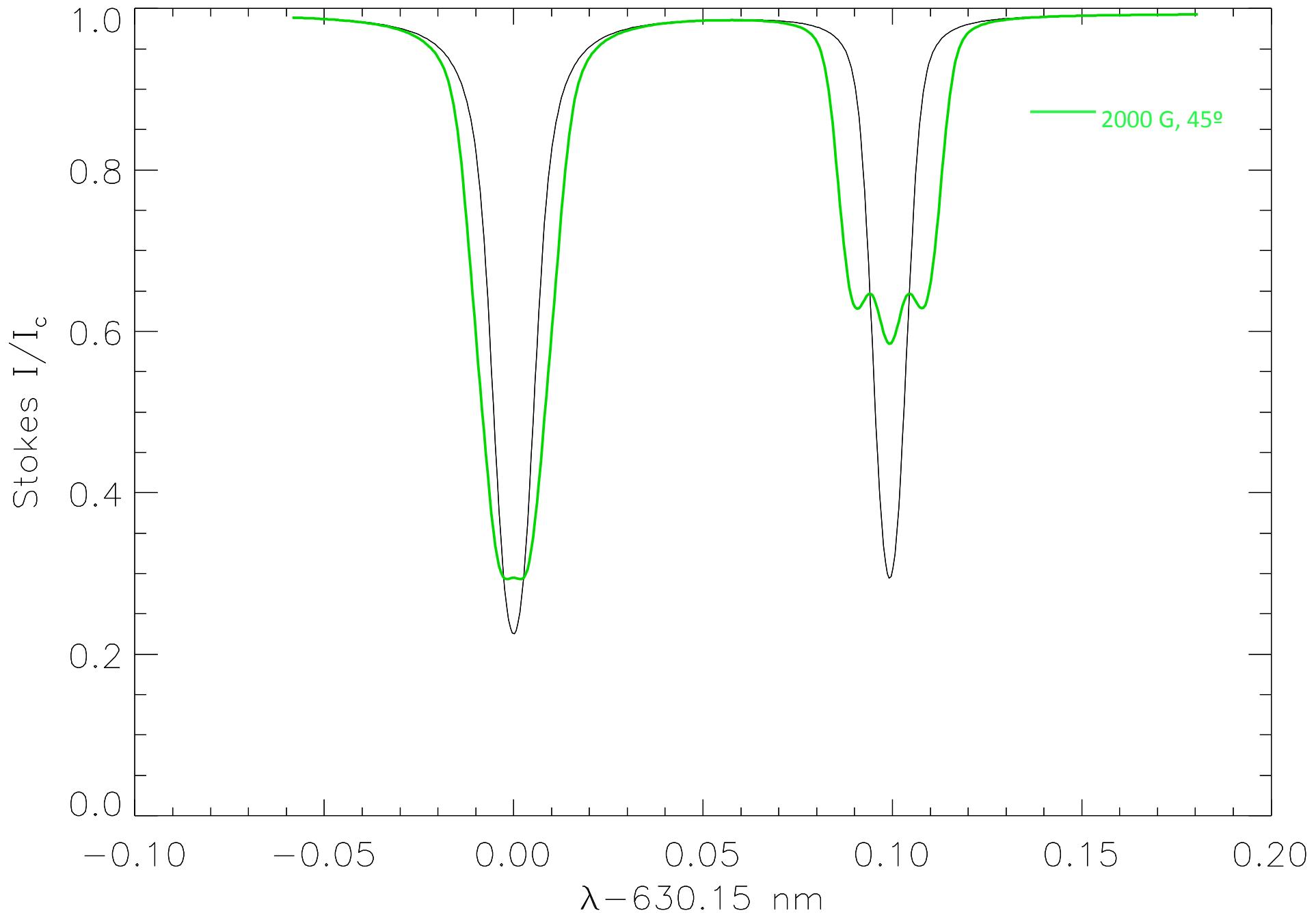
Pieter Zeeman (1865-1943)



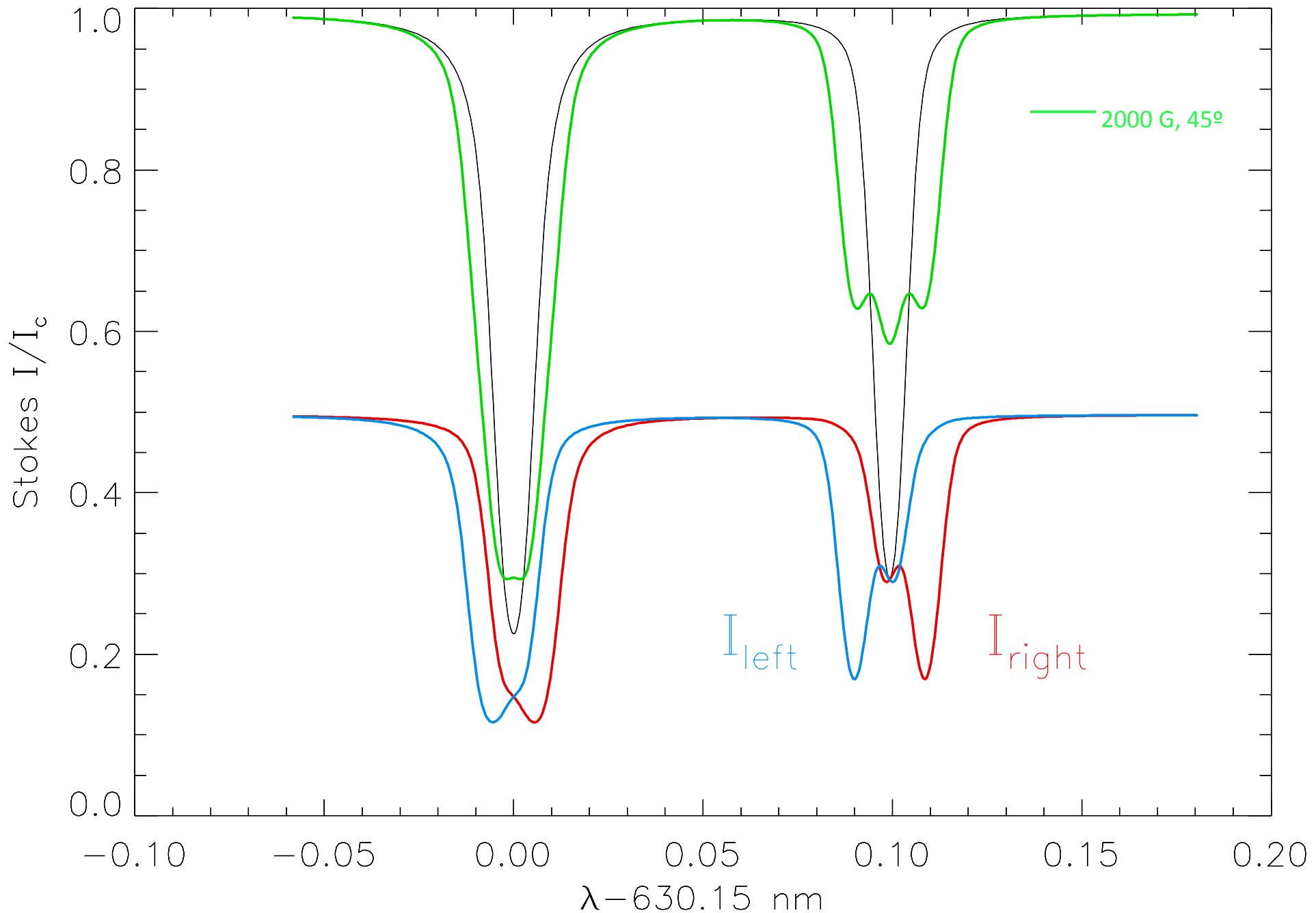
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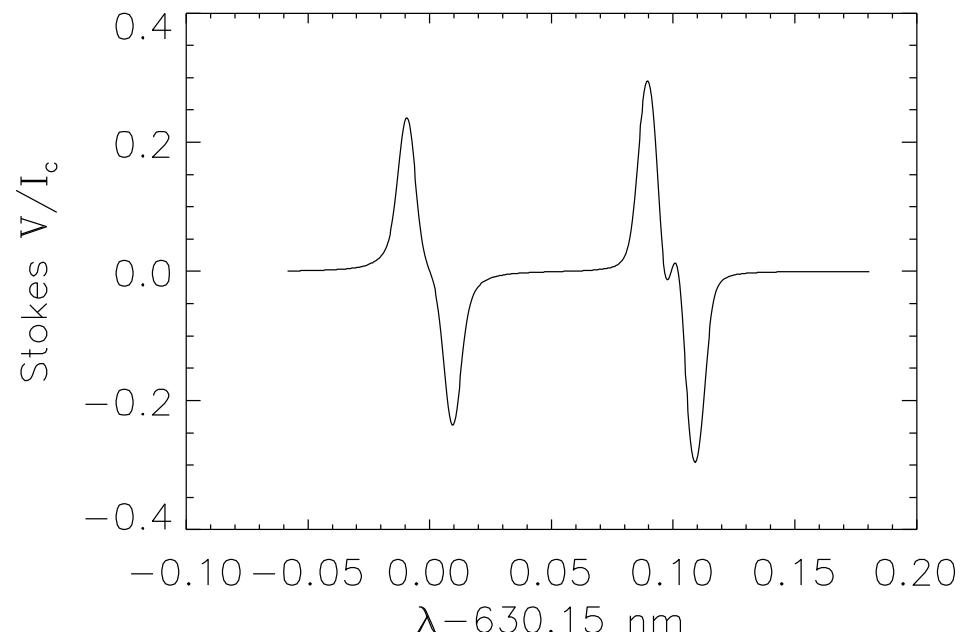
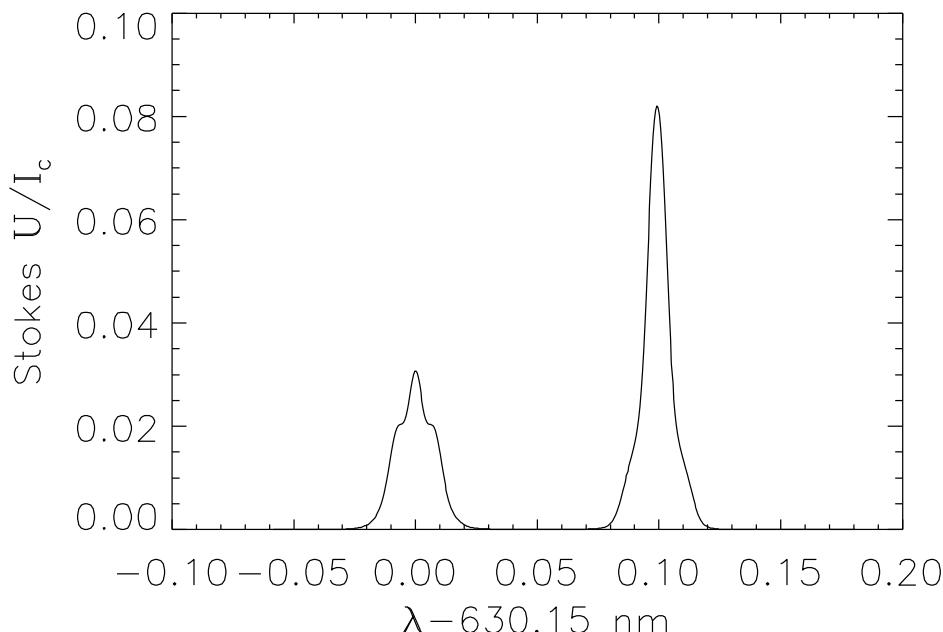
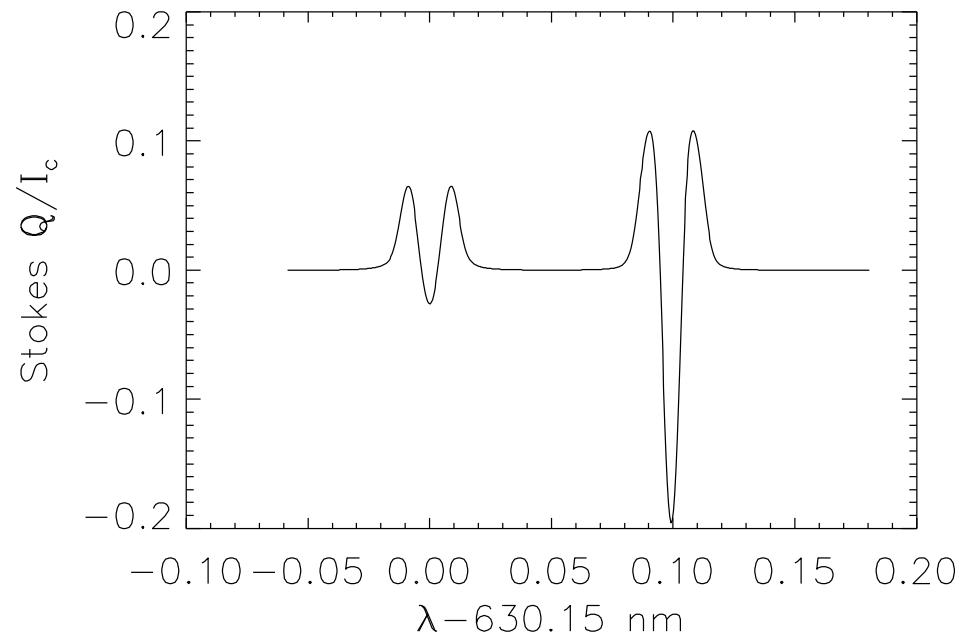
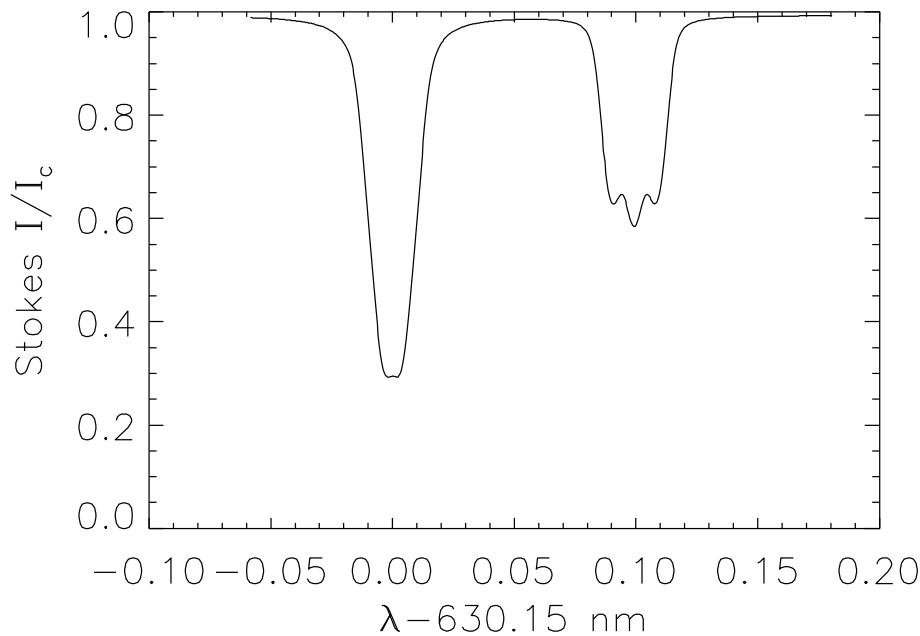
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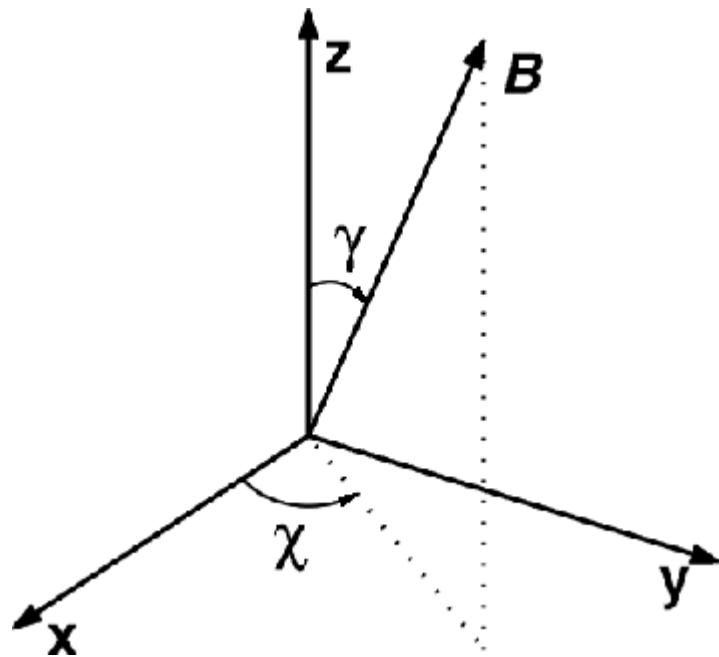
$$\frac{dI_\nu}{d\tau_c} = \kappa(I_\nu - S_\nu)$$

$$I_\nu \rightarrow \vec{I}_\nu = \begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix} \quad S_\nu \rightarrow \vec{S}_\nu = \begin{bmatrix} S_I \\ S_Q \\ S_U \\ S_V \end{bmatrix}^{LTE} = \begin{bmatrix} B_\nu \\ 0 \\ 0 \\ 0 \end{bmatrix}$$

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

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

# 1: The RTE: formal solution & approximations



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

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

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

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

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

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

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

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

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

# 1: The RTE: formal solution & approximations

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

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

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

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

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

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

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

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

## 2: The Response Functions

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

- 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  $x = a_i(\tau_j)$ ?

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

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

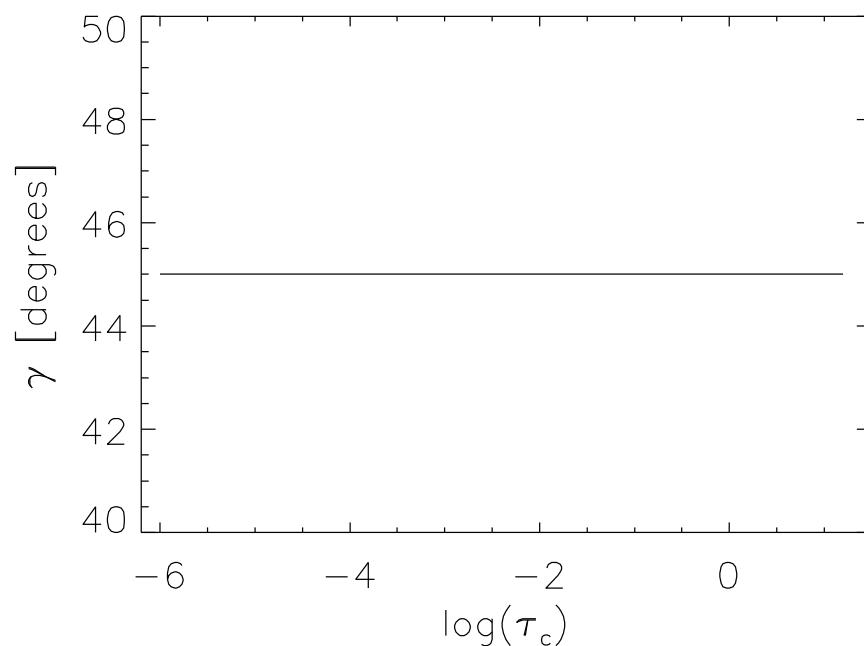
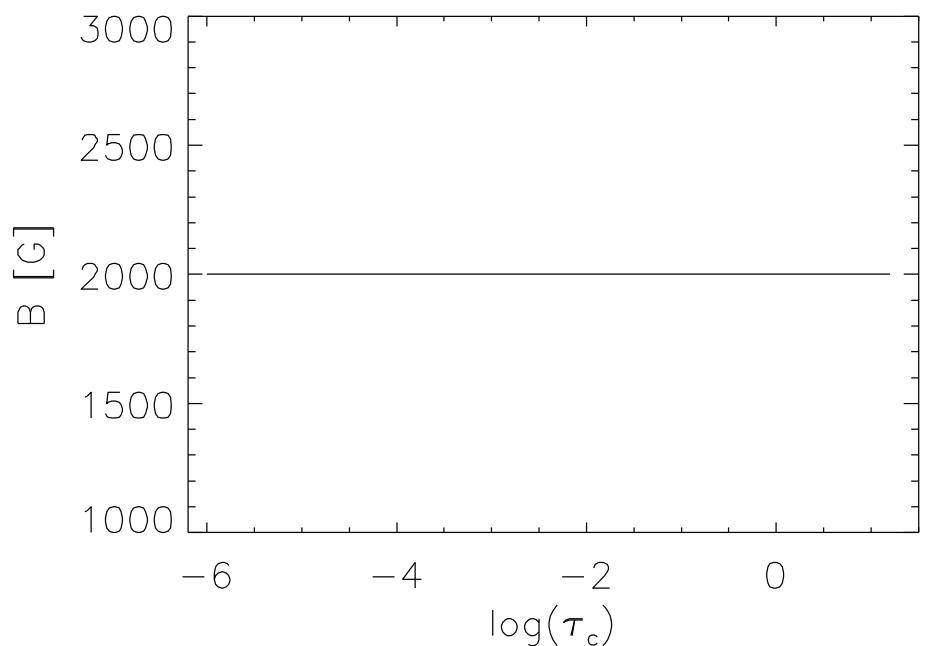
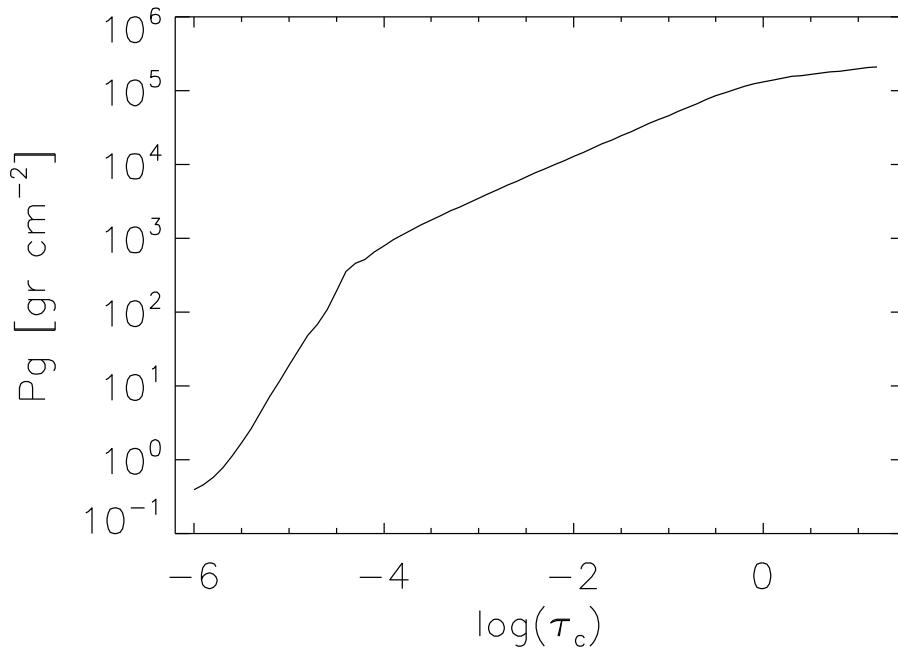
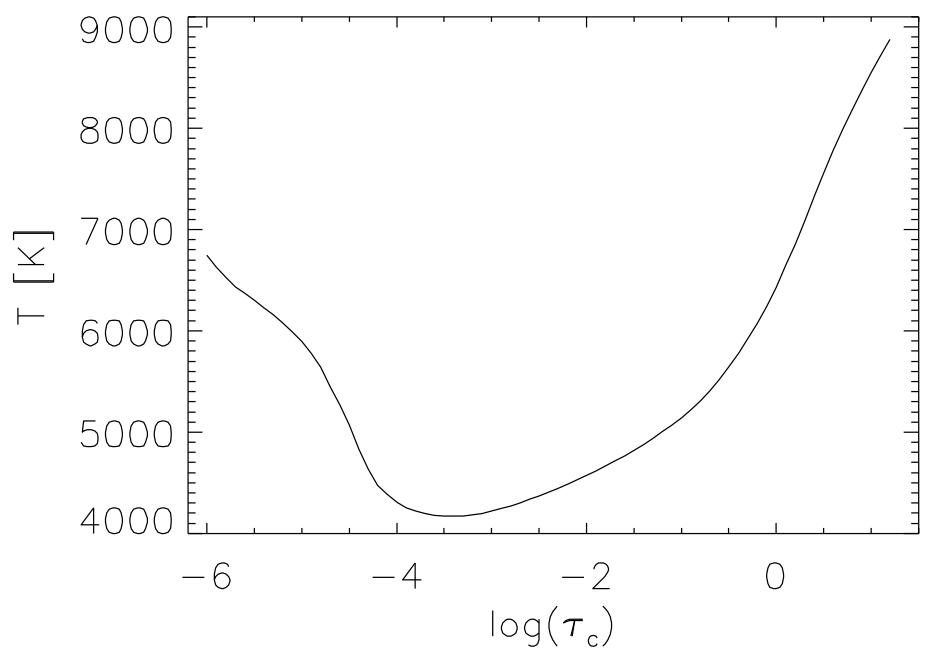
$$\delta\vec{I}_\nu = \int_0^{\tau_c} \overline{\overline{O}}(\tau_c) \overline{\overline{K}} \tilde{\vec{S}} d\tau_c \equiv \int_0^{\tau_c} R_x \delta x d\tau_c$$

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

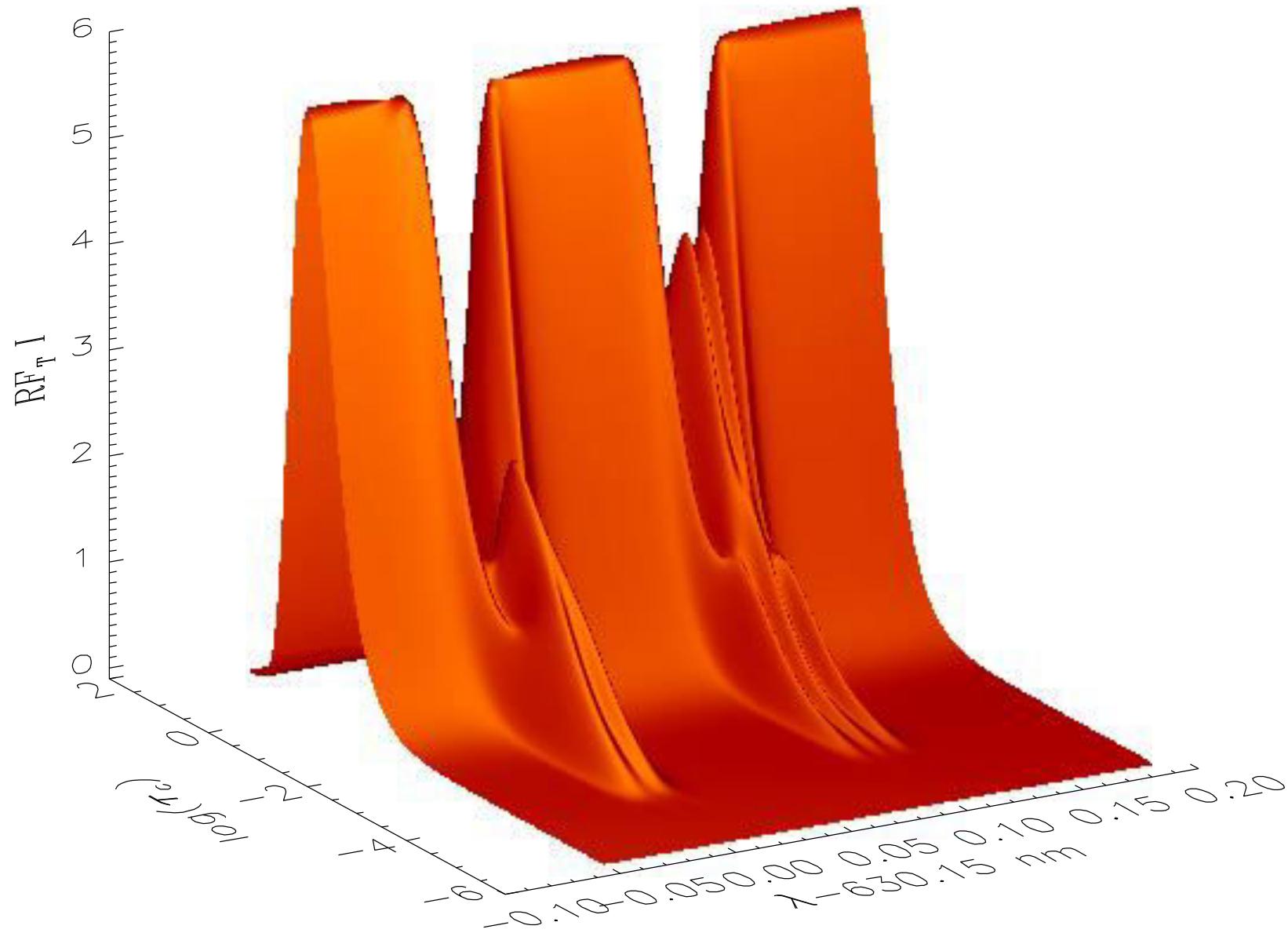
$$\tilde{\vec{S}}_\nu = \overline{\overline{K}}^{-1} \overline{\overline{\delta K}} (\vec{I}_\nu - \vec{S}_\nu) - \overline{\overline{\delta S}}_\nu$$

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

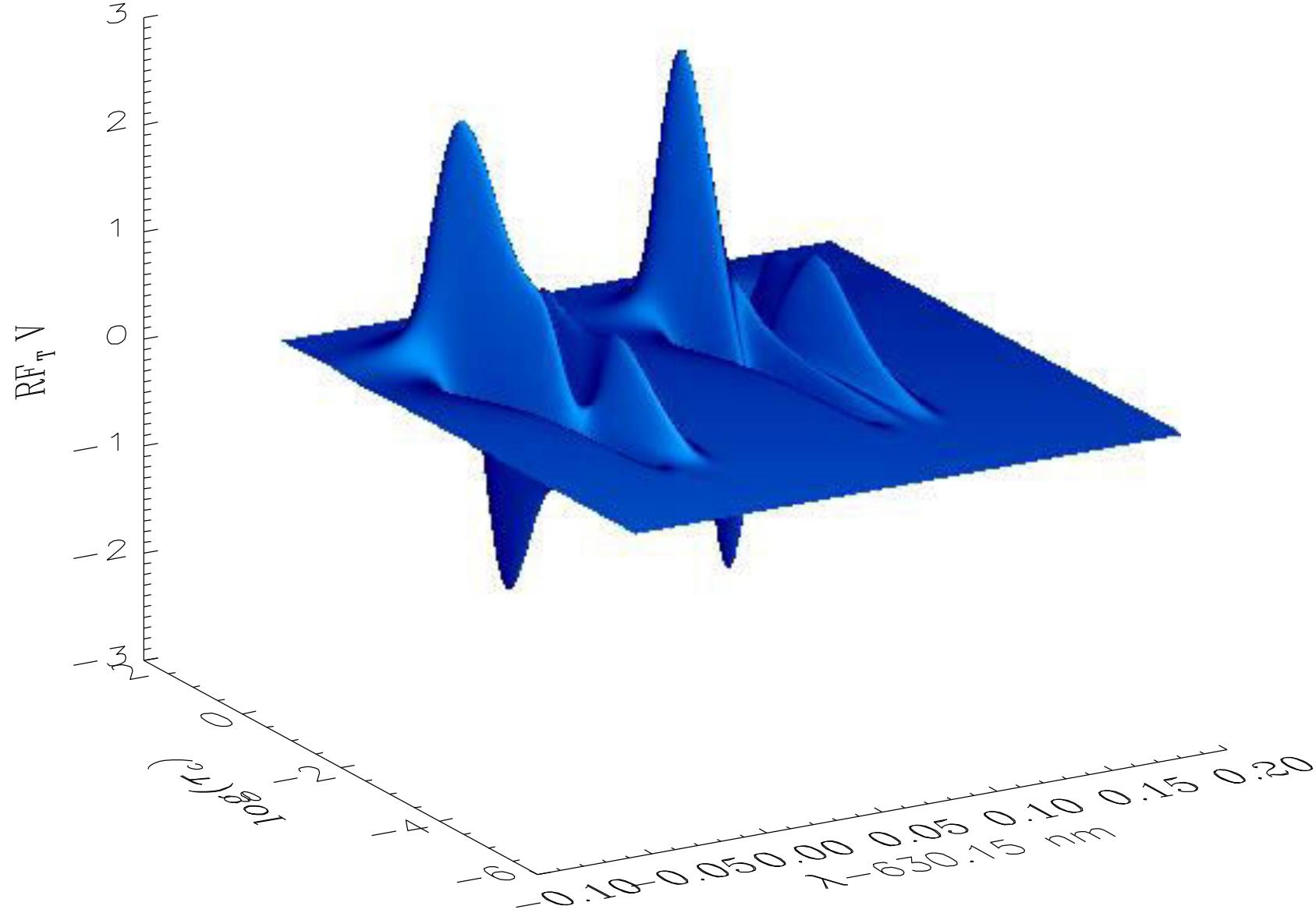
## 2: The Response Functions



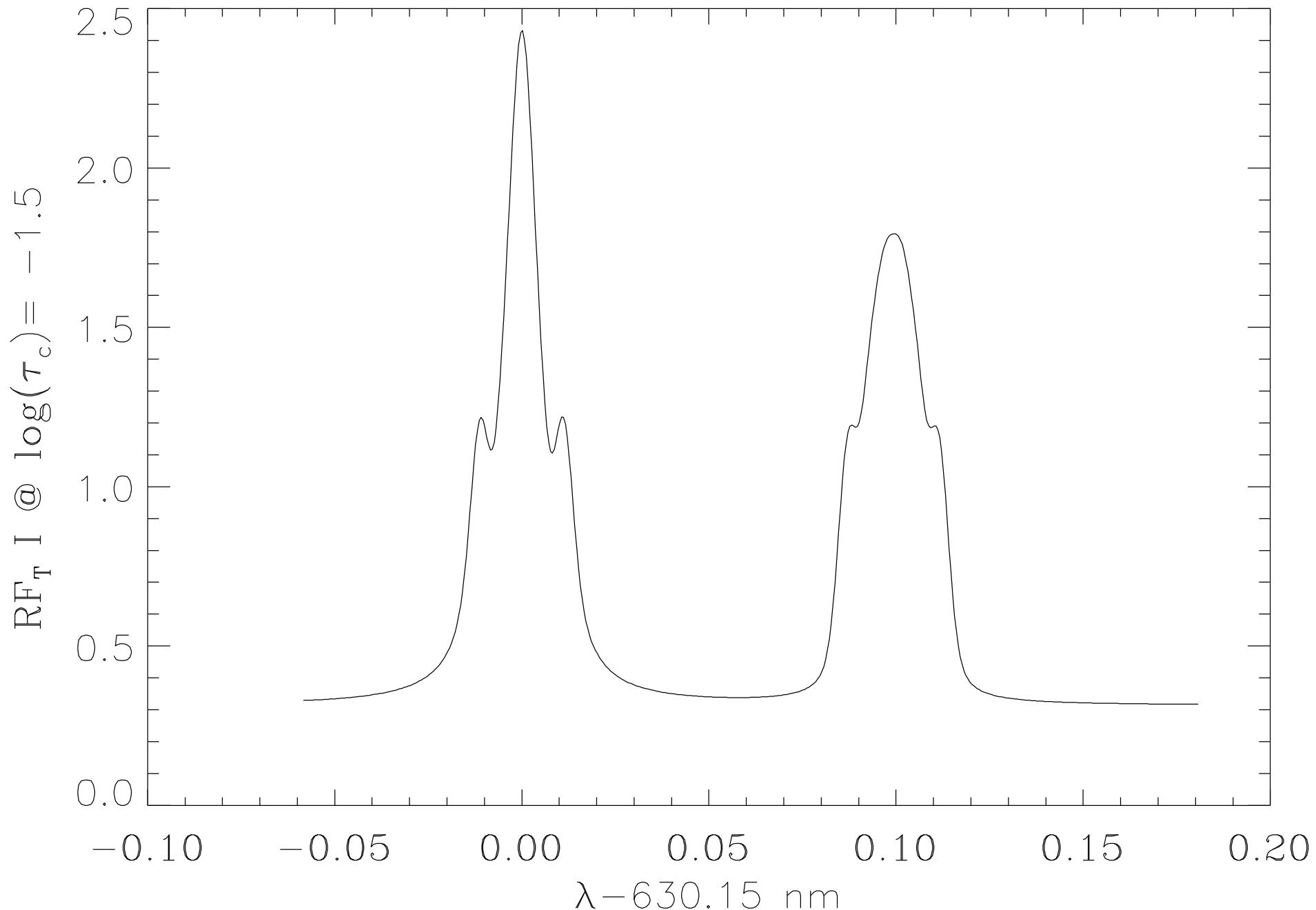
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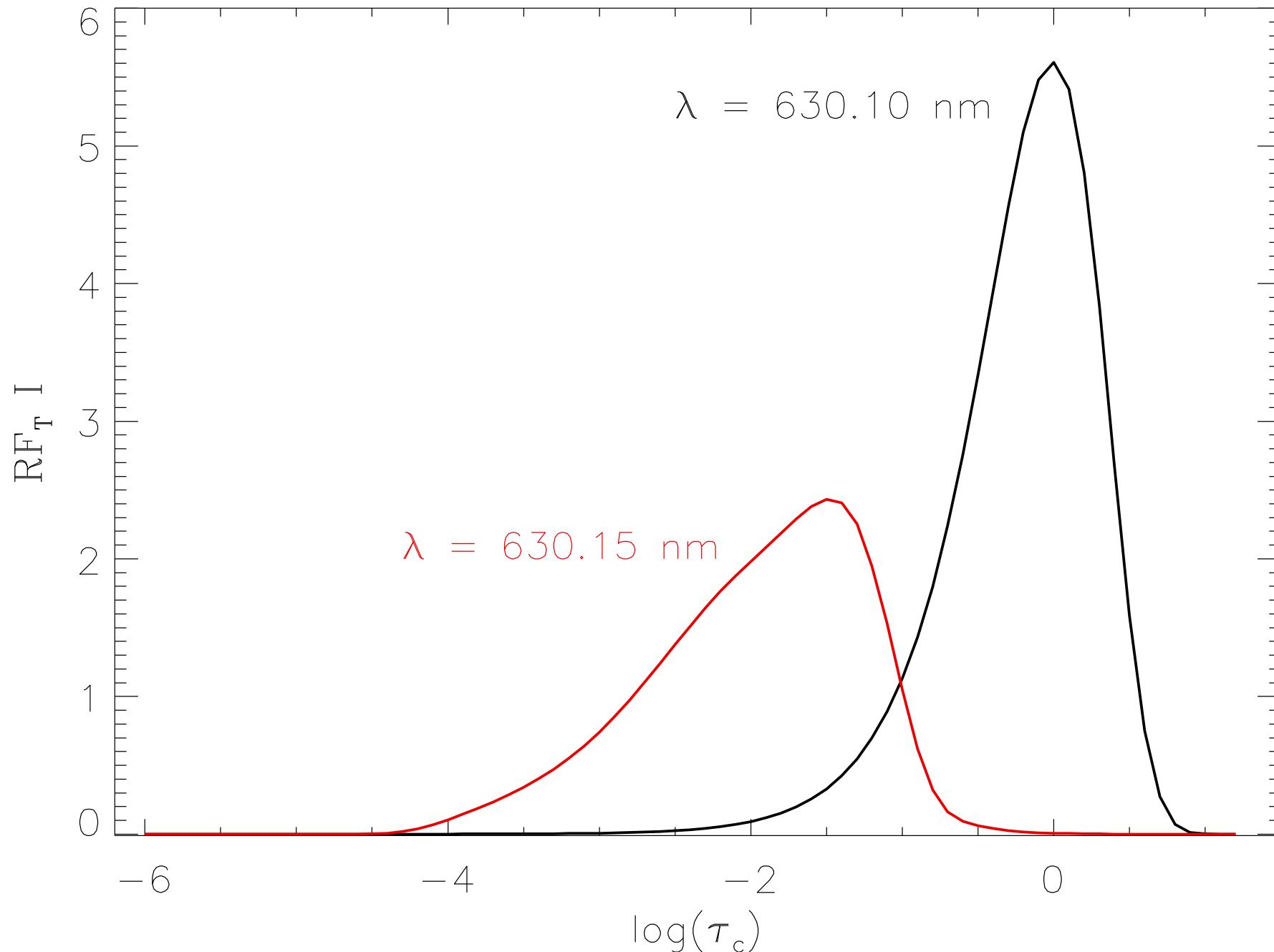
## 2: The Response Functions



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## 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)

$$\vec{I}_\nu \text{ & } \vec{R}_x$$

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

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

### 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 one 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

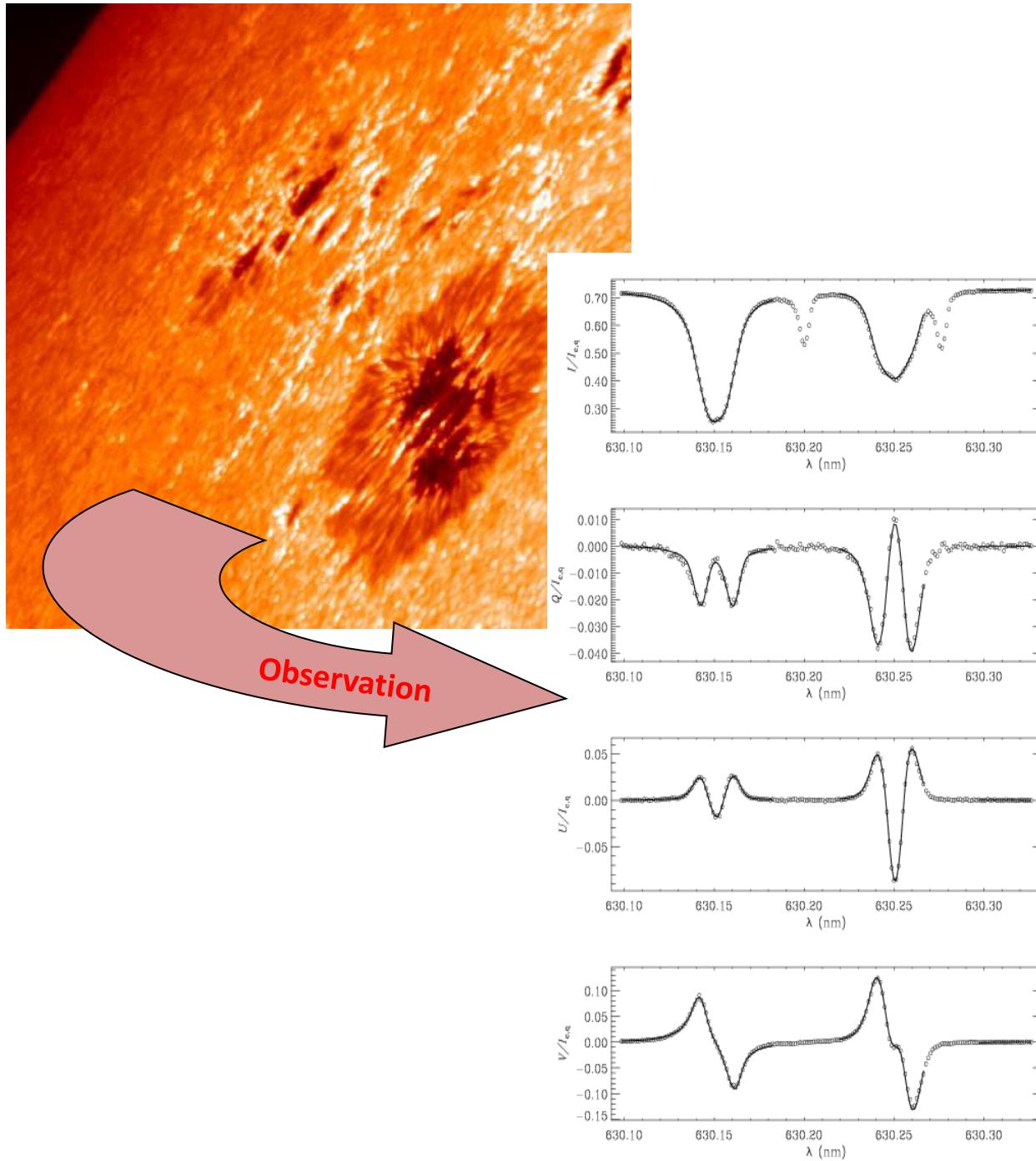
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$$g(t) = \int_a^b K(t, s) f(s) ds$$

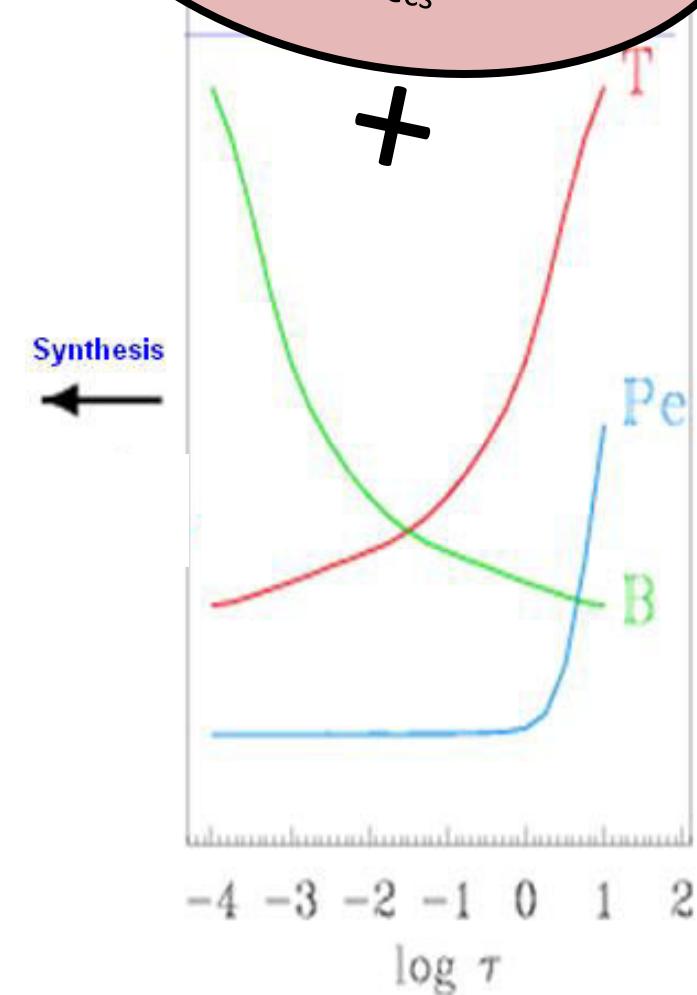
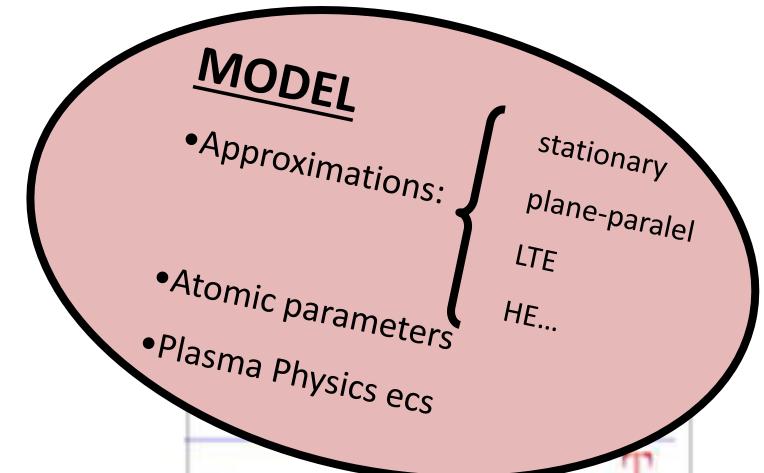
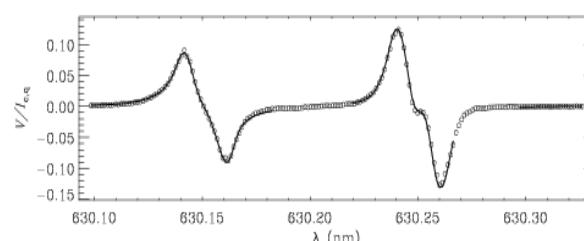
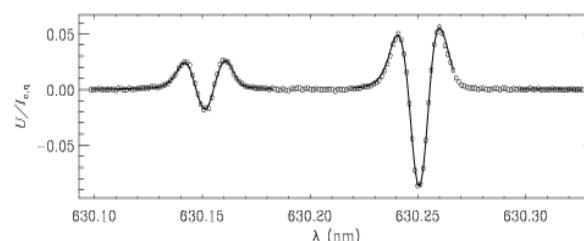
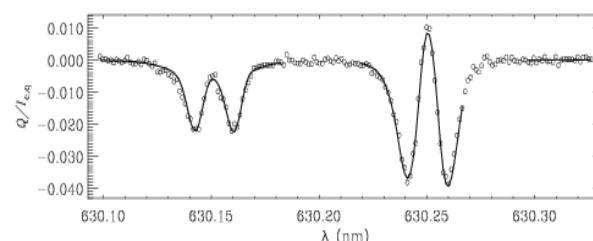
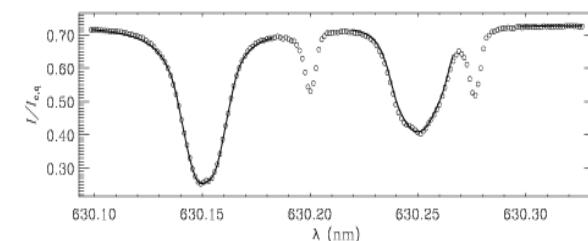
$f(s)$  become smoothed by the kernel  $K(t, s)$

- 1) Small  $g(t)$  perturbations are compatible with huge changes in  $f(s)$
- 2) Smoothing means lost information, then “recover”  $f(s)$  is impossible
- 3) We have a discrete set of  $g(t)$  values and we’d wish a function  $f(s)$

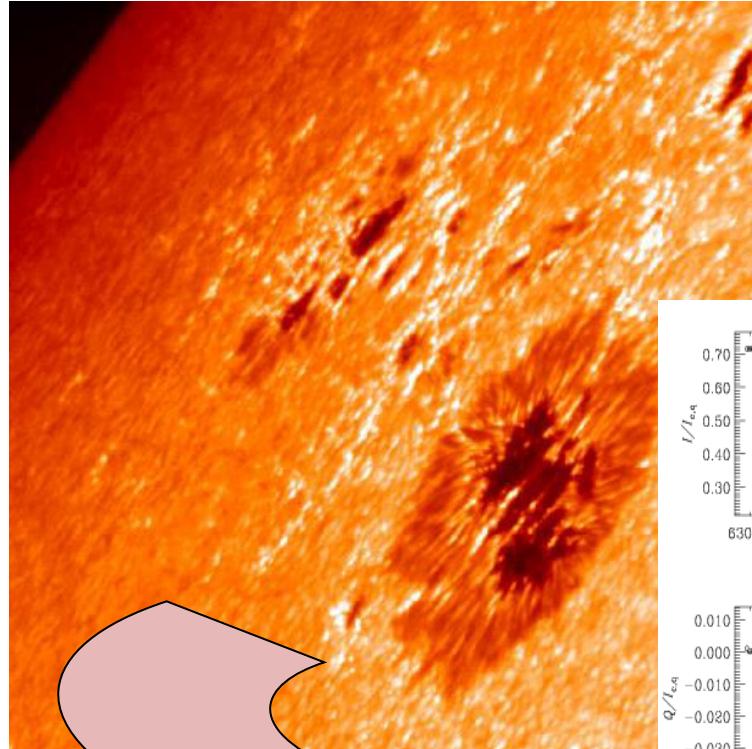
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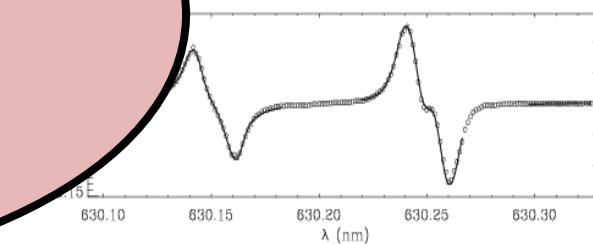
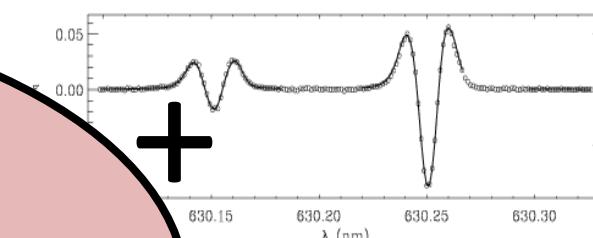
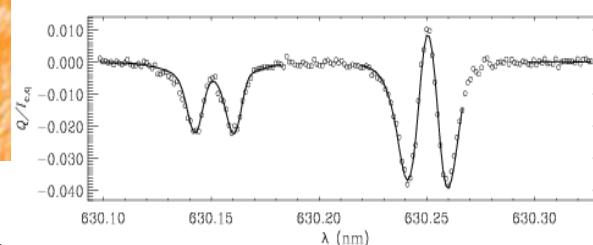
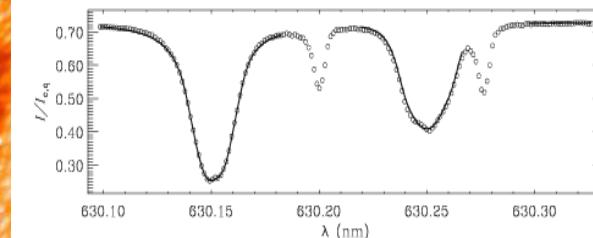
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**Observation**

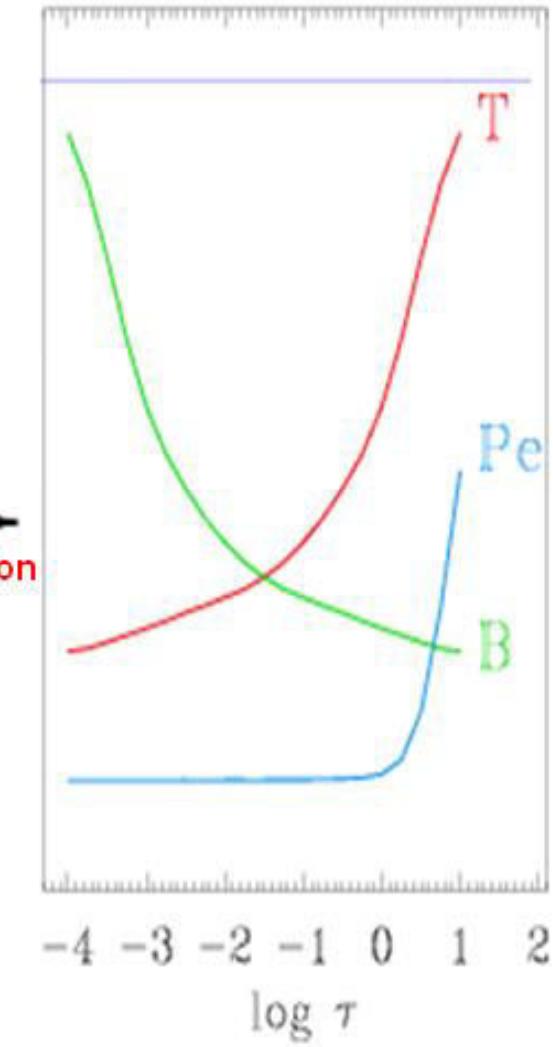
#### MODEL

- Approximations:
  - { stationary
  - plane-parallel
  - LTE
  - HE...
- Atomic parameters
- Plasma Physics ecs

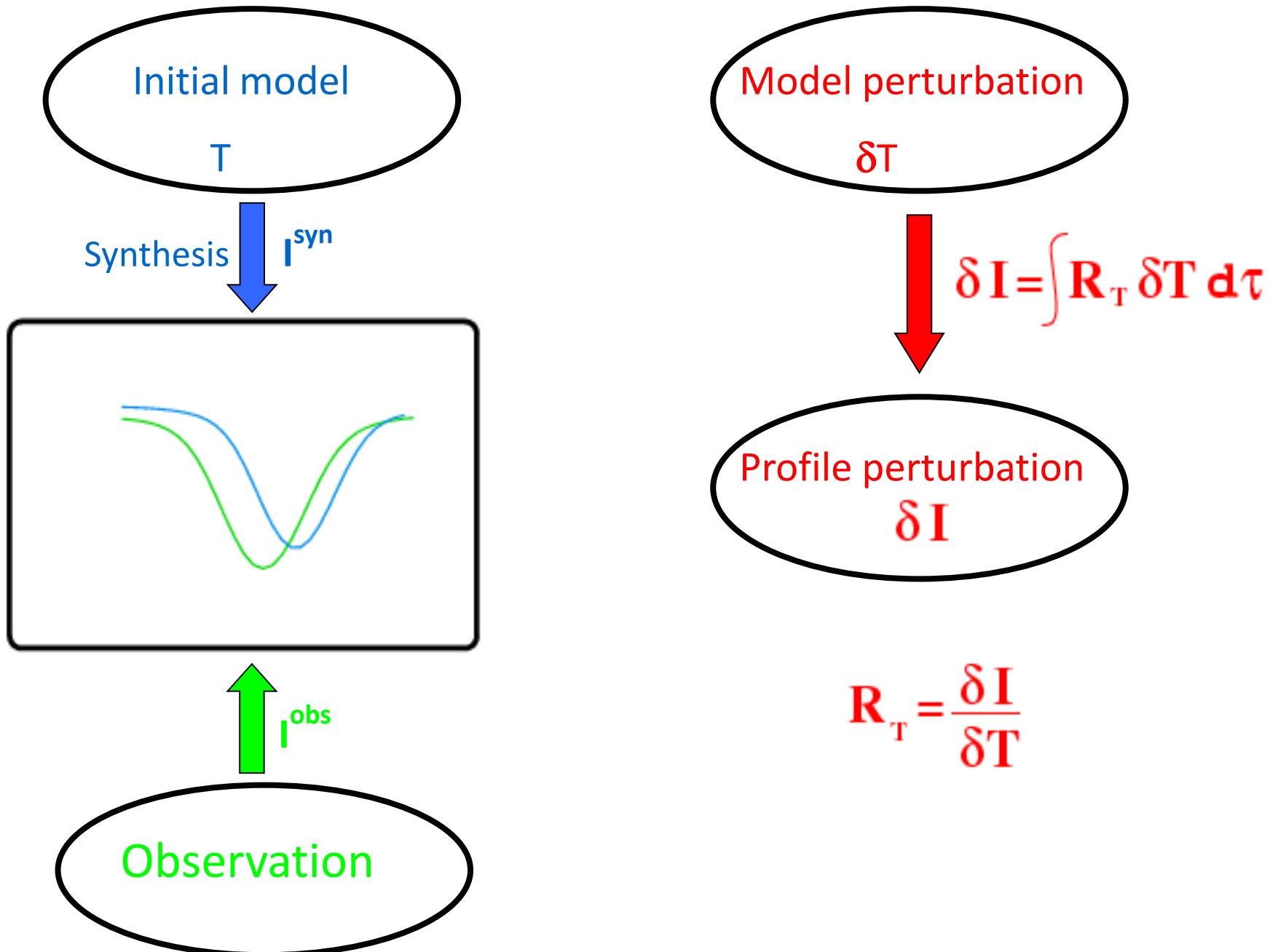


- The model (except free parameters values ) must be known a priori
- We only fit the free parameters

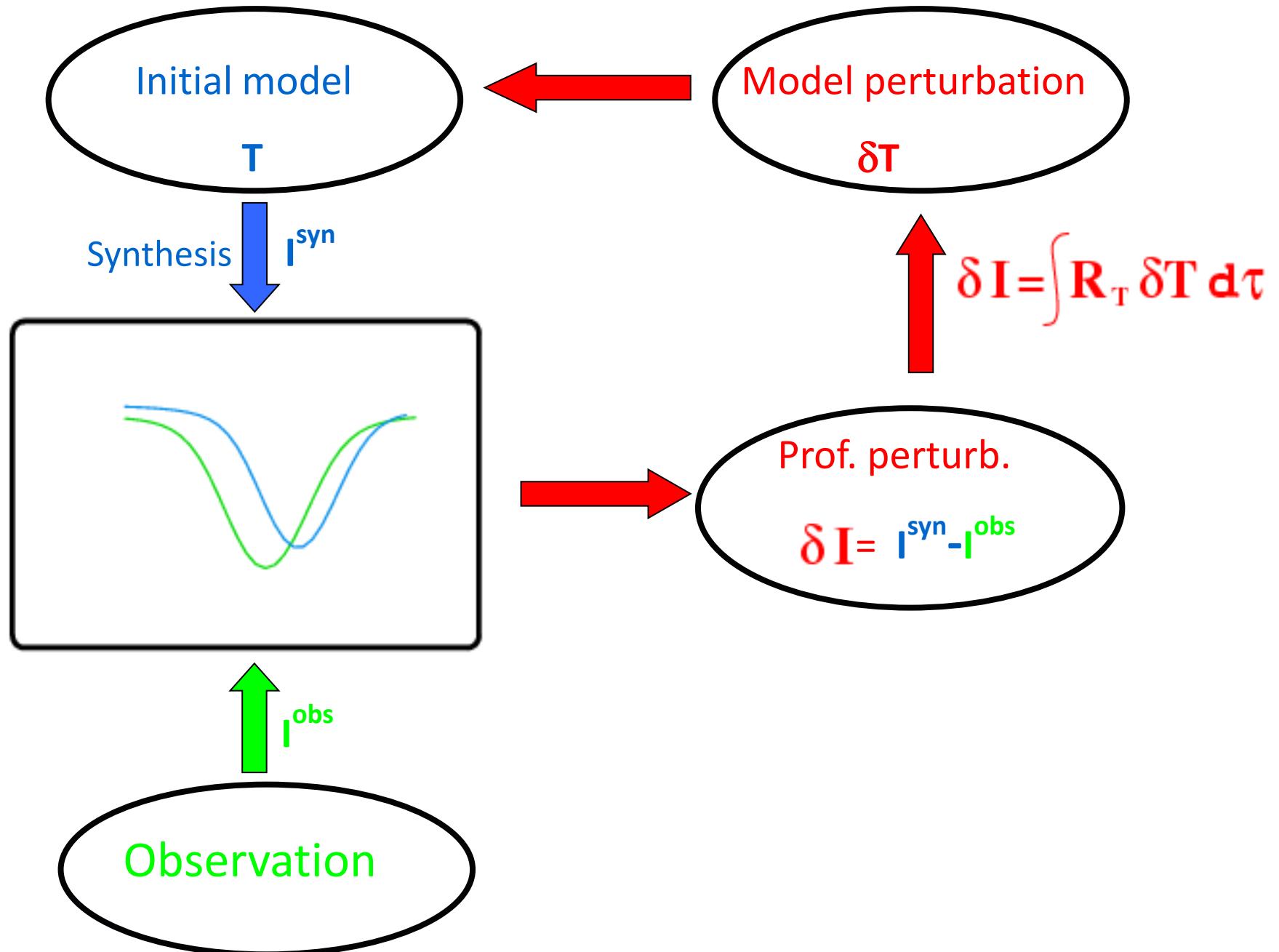
**Inversion**



## 4: The SIR code



## 4: The SIR code



## 4: The SIR code

- Inversion driven by  $\chi^2$ -minimization

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

- Minimization: 2nd order Levenberg-Marquardt algorithm

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

## 4: The SIR code

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

Least squares

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

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

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

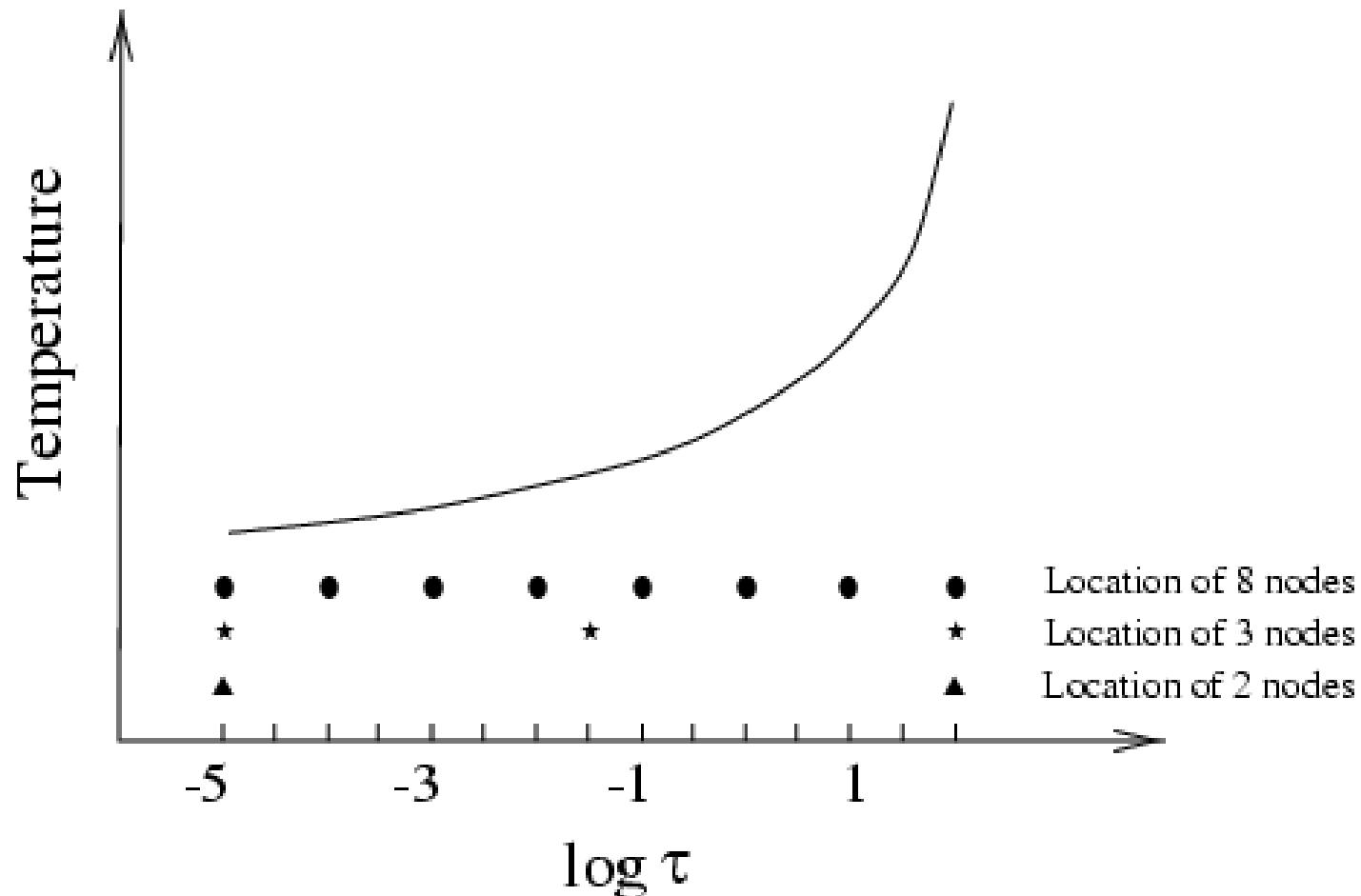
## 4: The SIR code

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

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  $A$

- Very large (1)
- Singular (2)

- 1) Sequential increase of unknown number
- 2) Singularities elimination through SVD (Singular Value Decomposition)

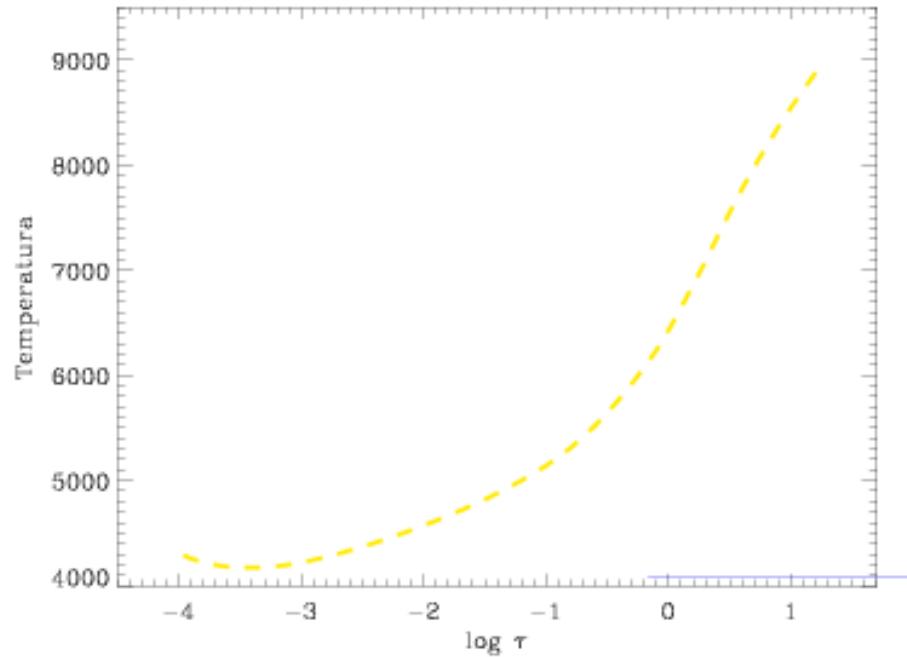
$$A = U W V^T \text{ with } U \text{ & } V \text{ orthonormal matrix}$$

$$\text{y } W = \text{diagonal}(w_{jj})$$

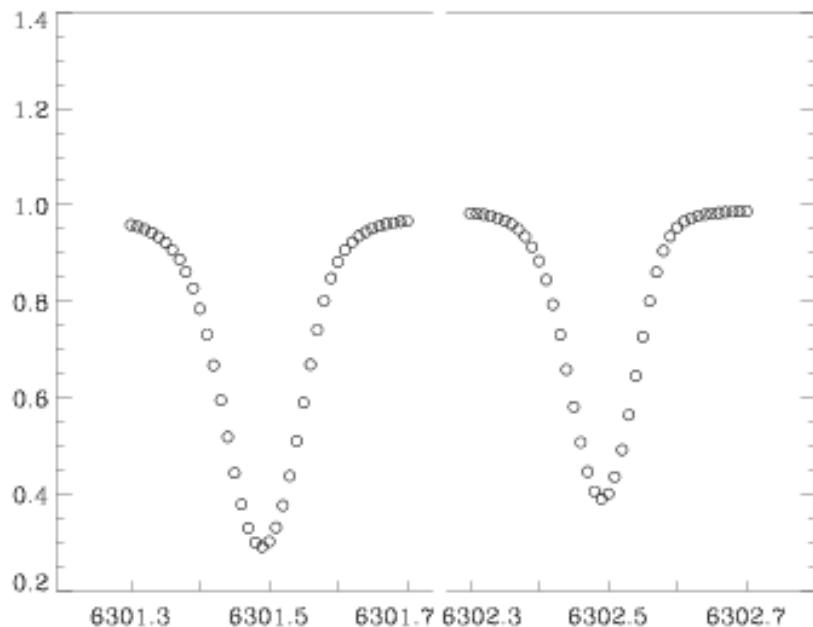
$$A^{-1} = V W^{-1} U^T \text{ with } W^{-1} = \text{diagonal}(1/w_{jj})$$

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

## 4: The SIR code

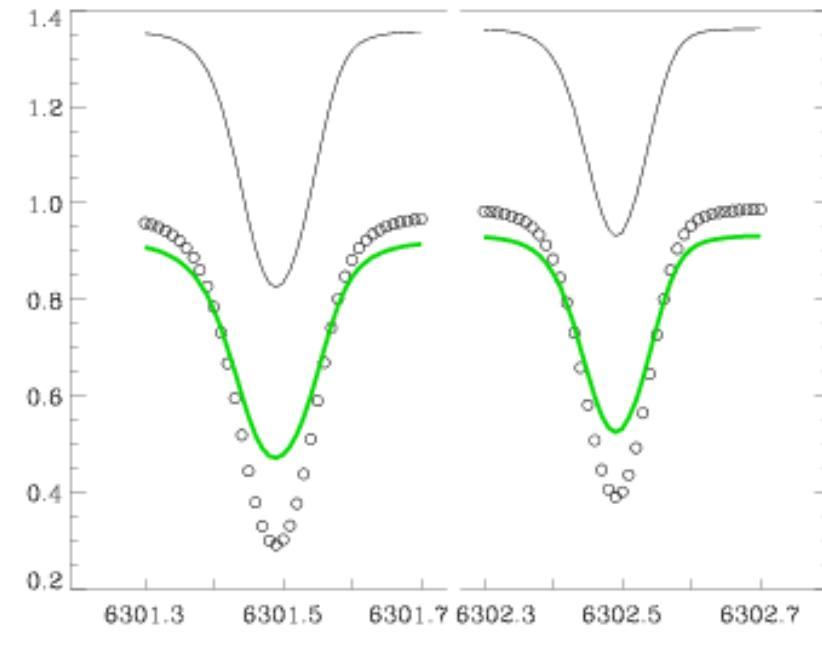
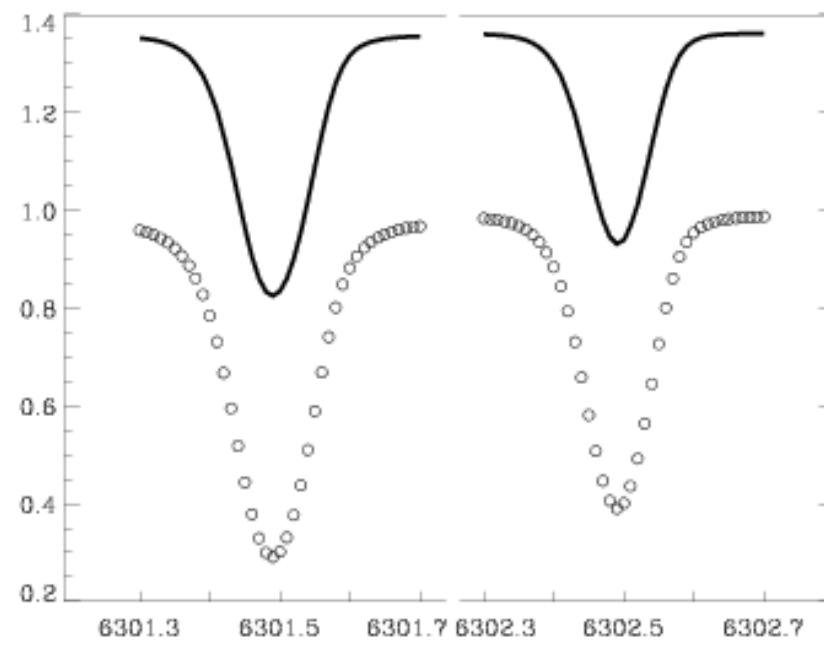
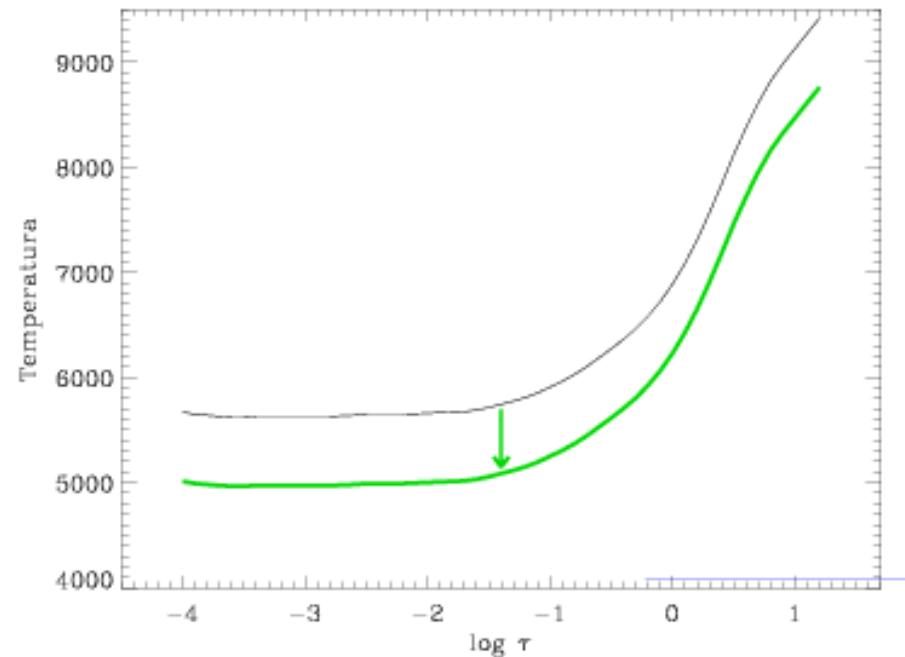
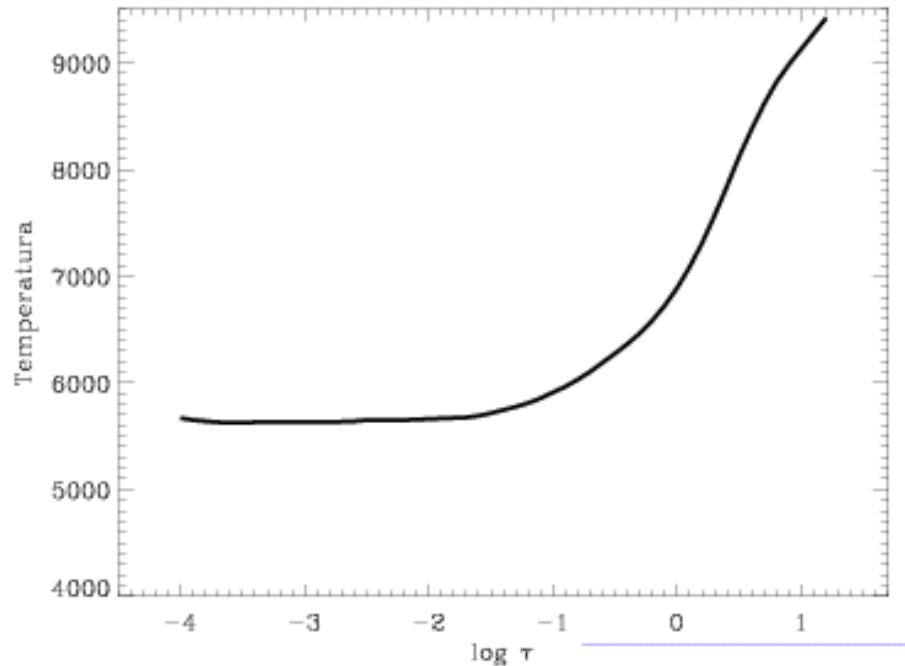


The “real” SUN

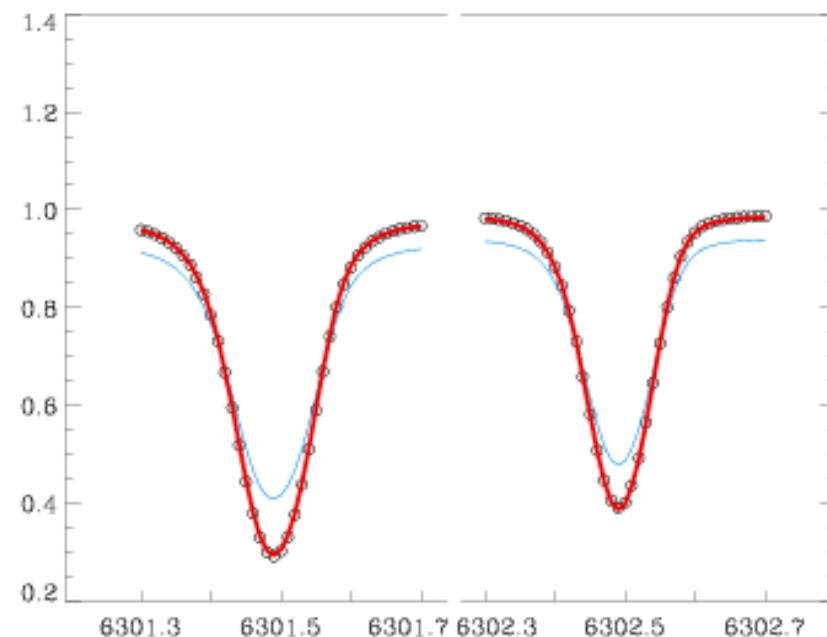
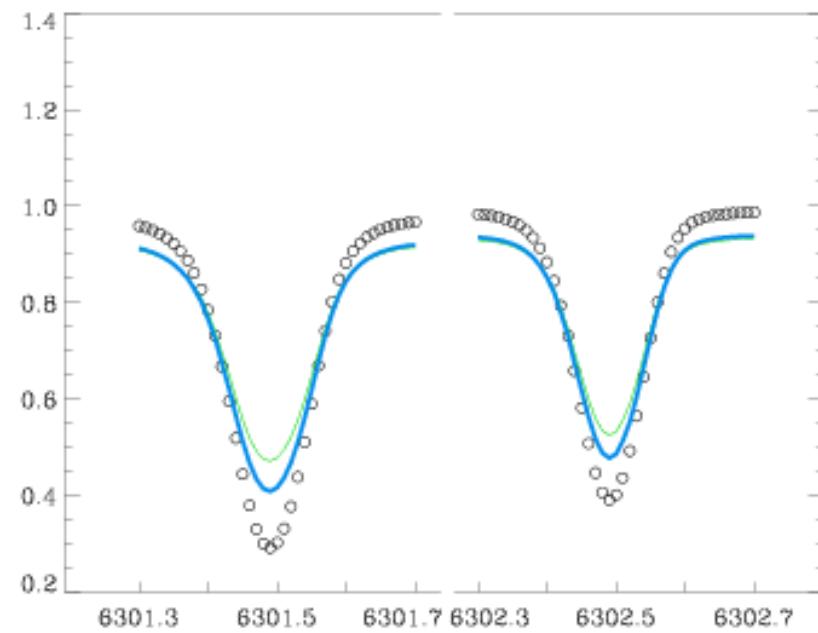
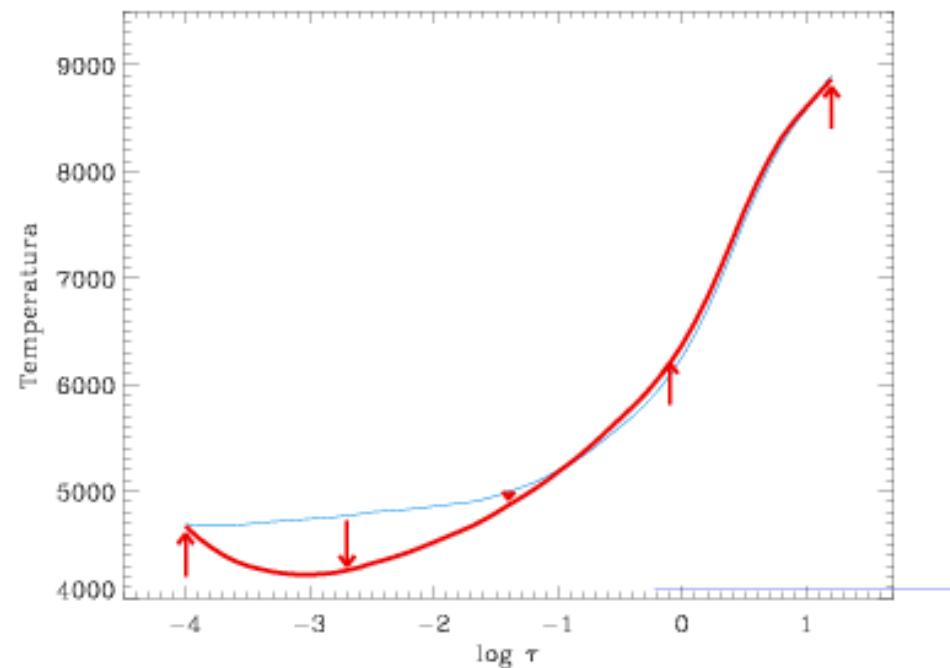
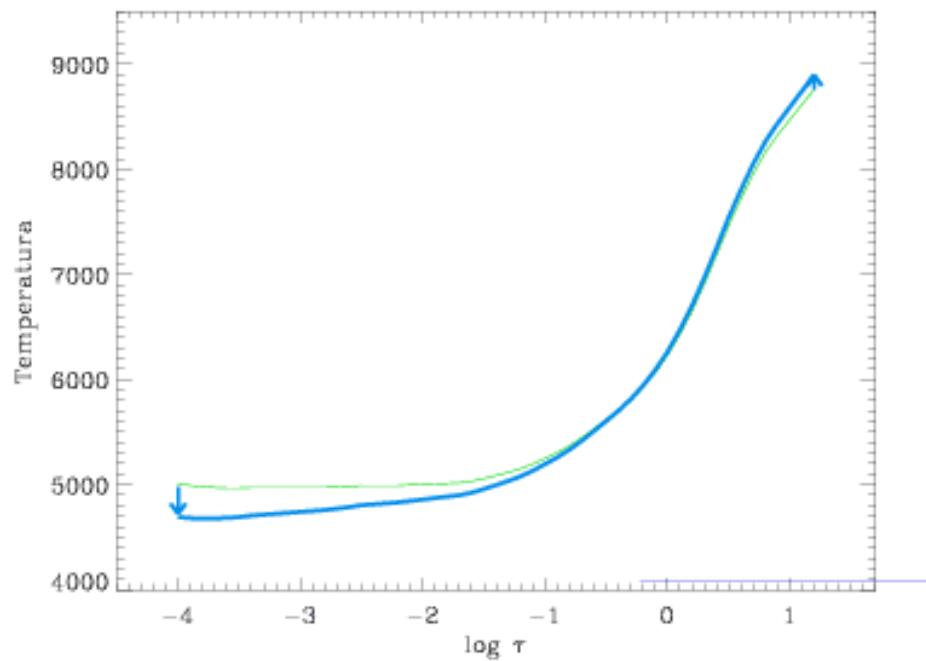


Synthetic  
“observations”

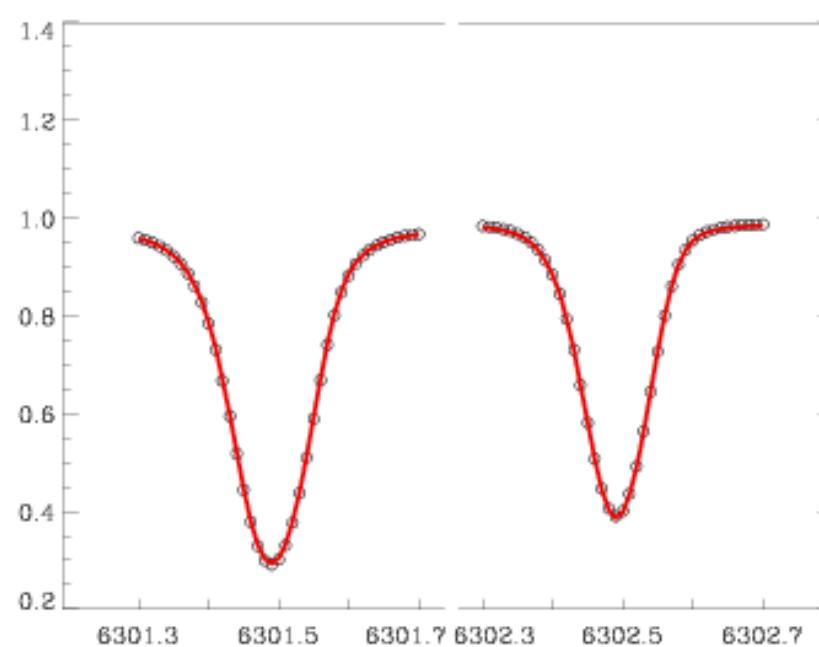
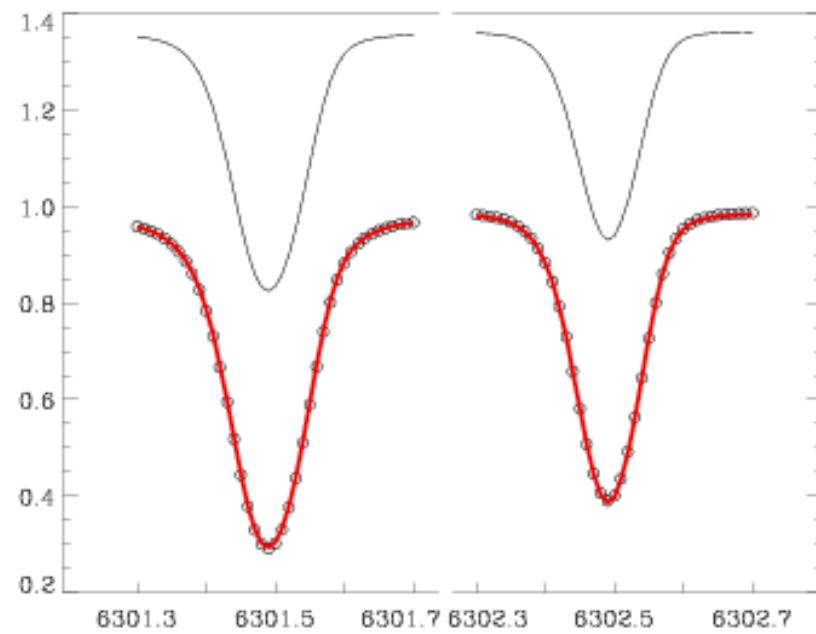
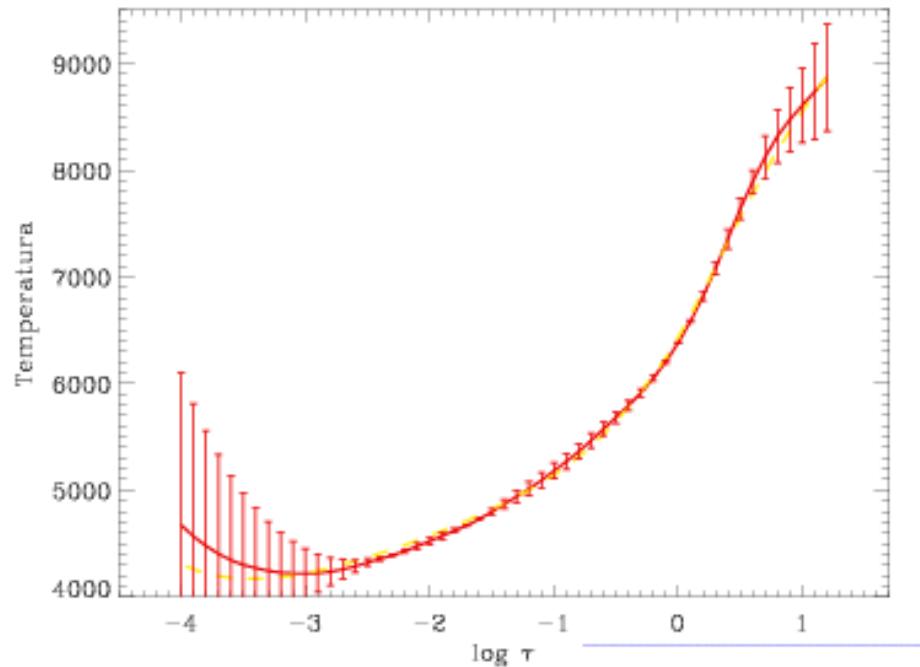
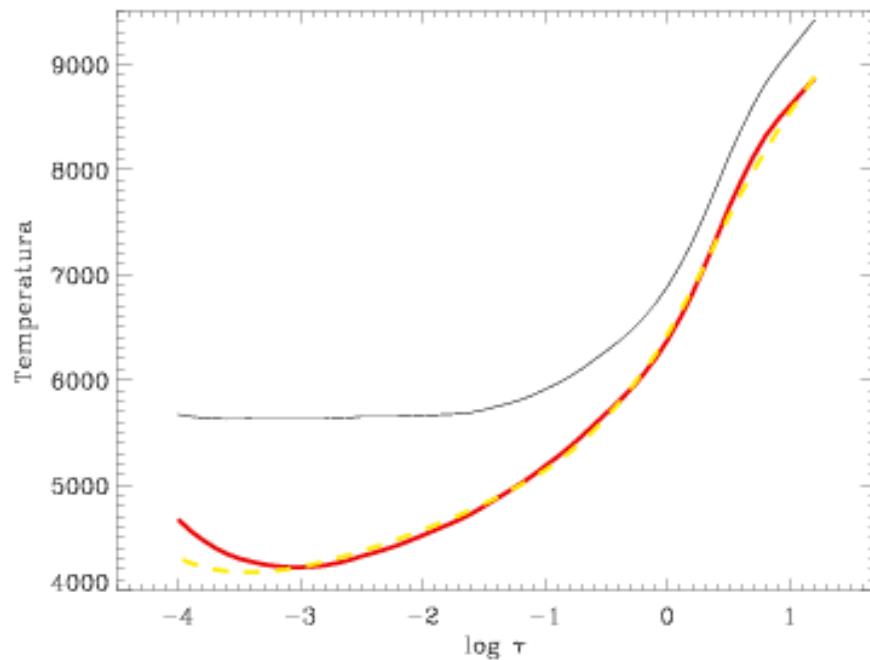
## 4: The SIR code



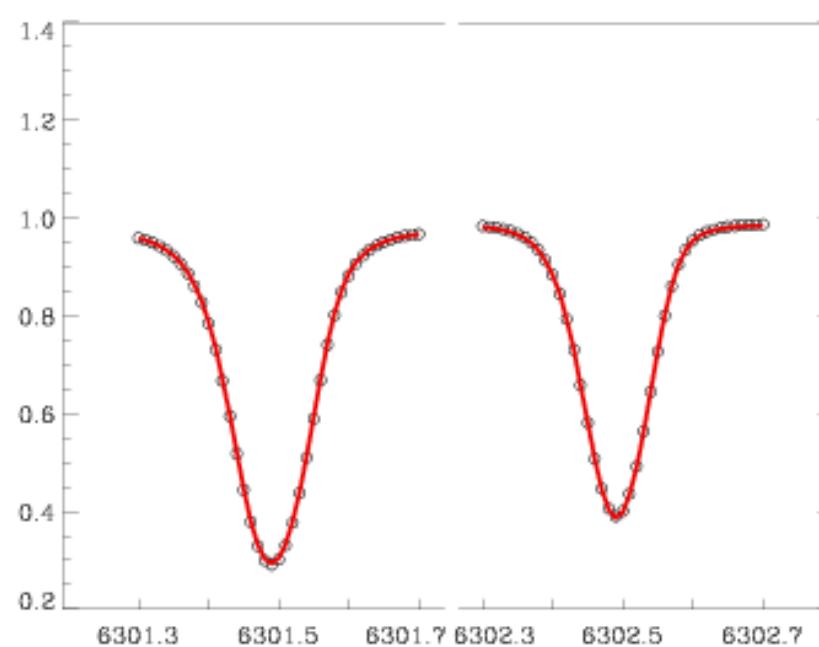
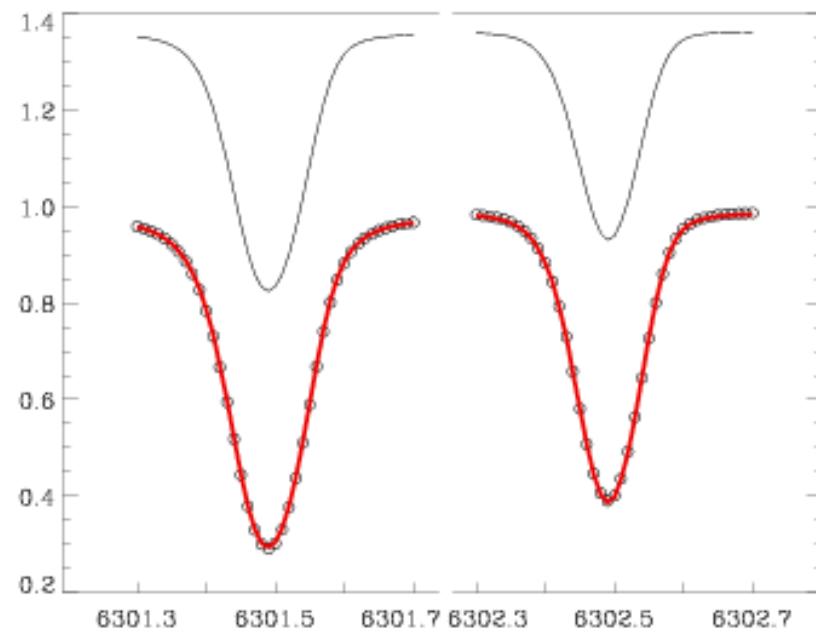
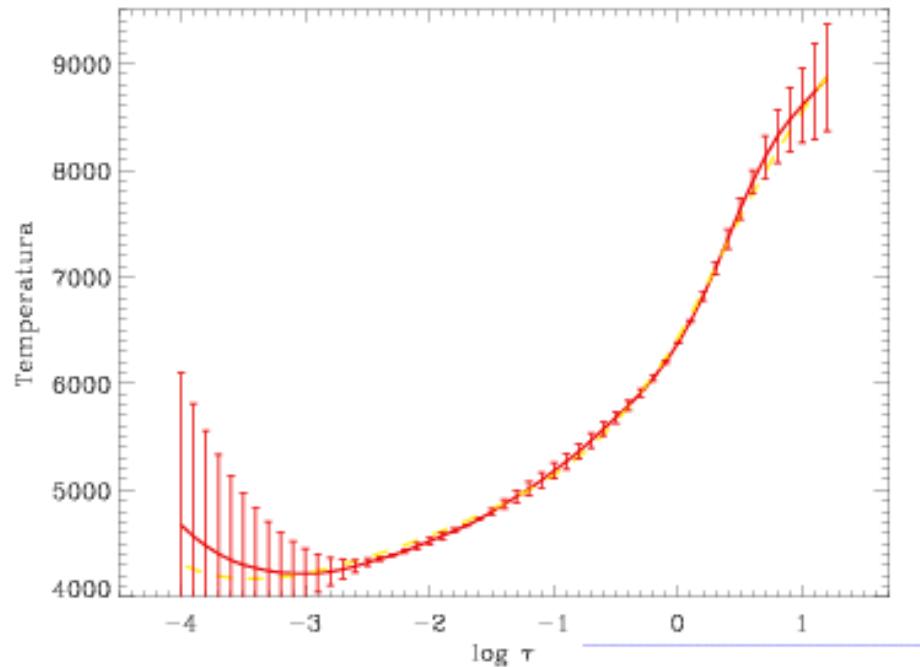
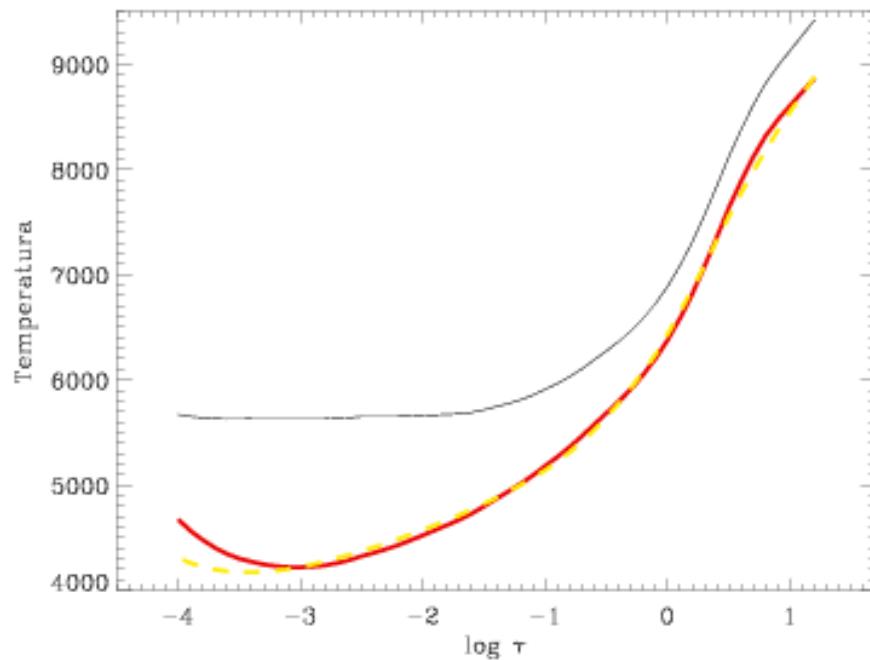
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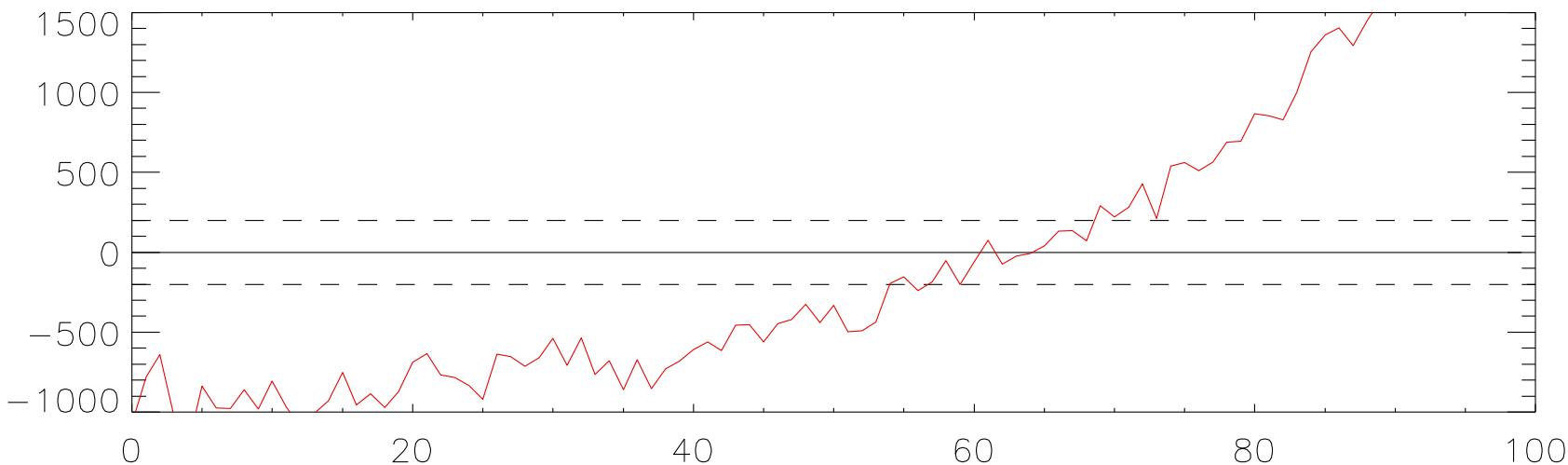
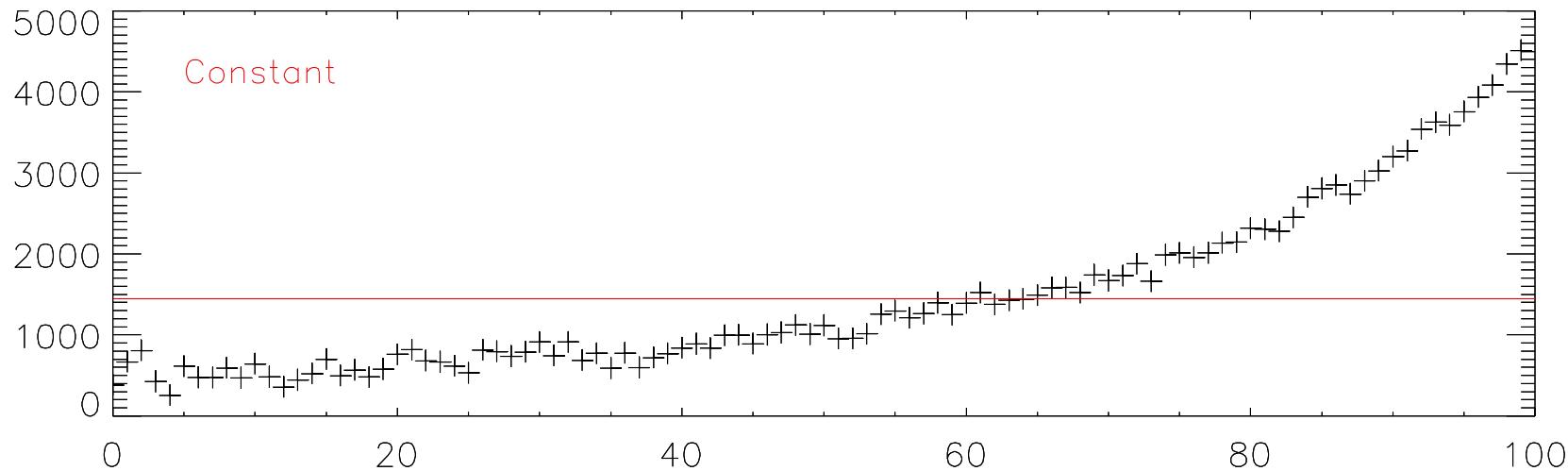


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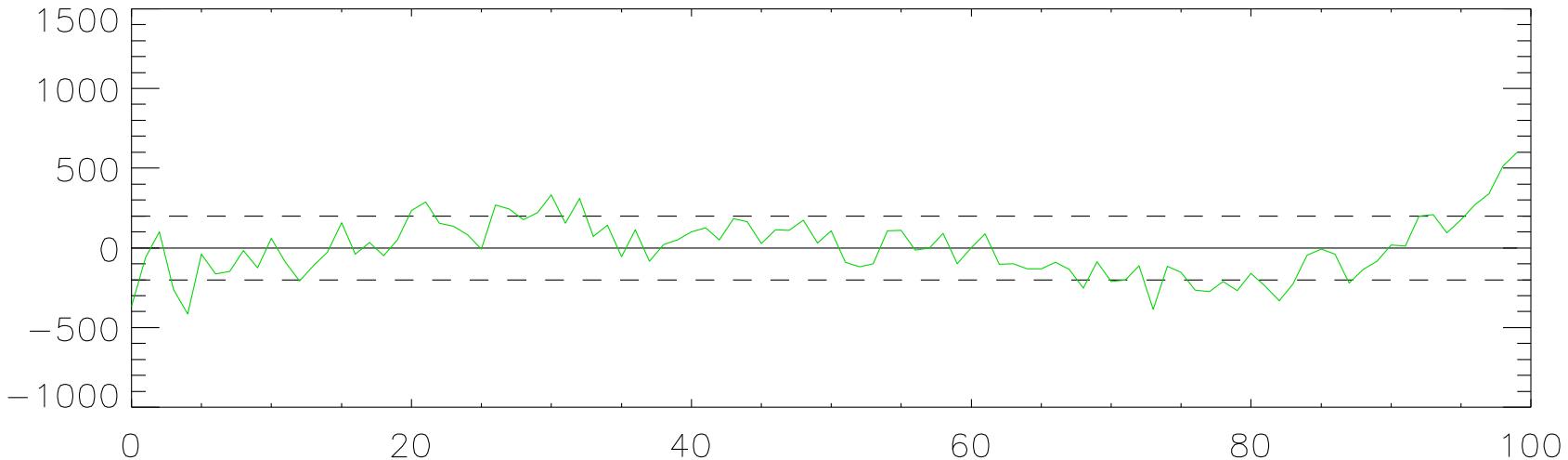
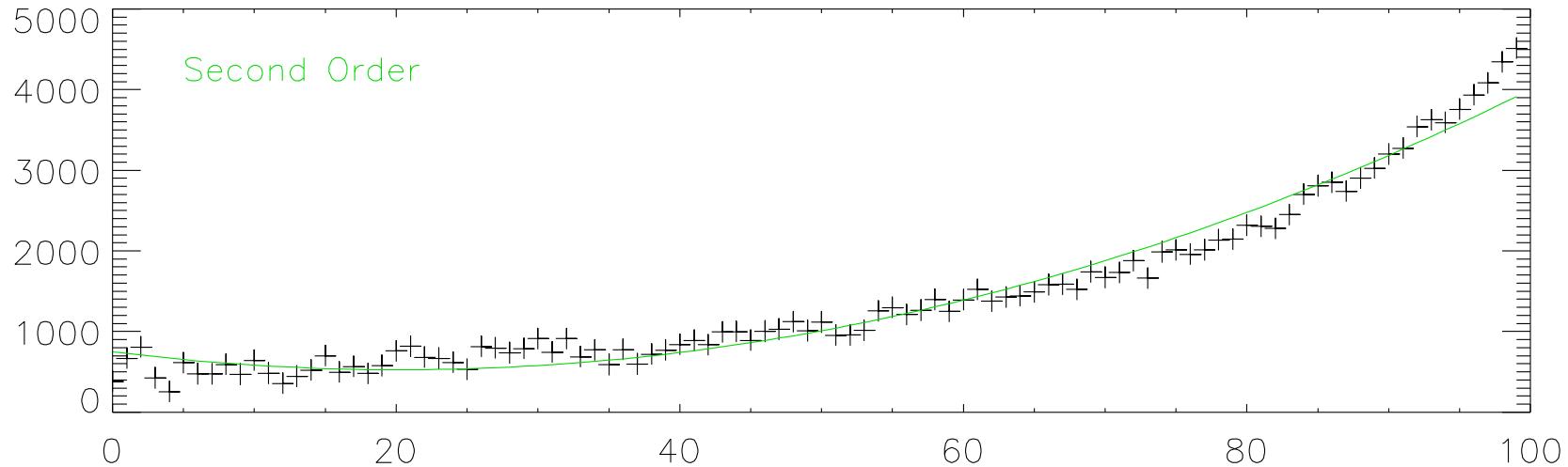
## 4: The SIR code

Unicity?



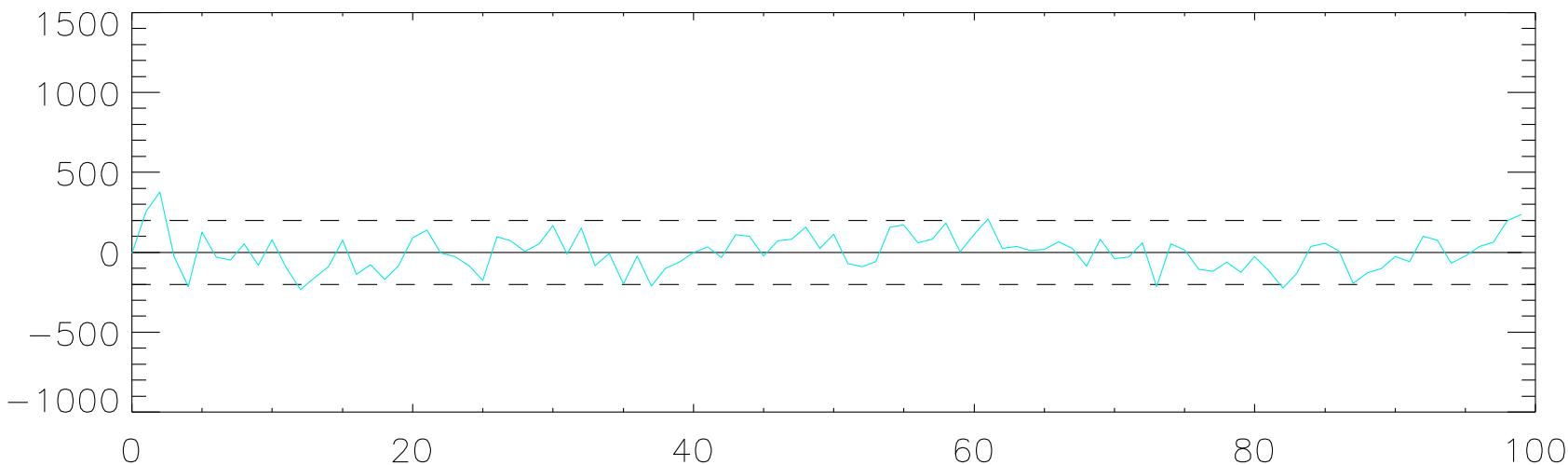
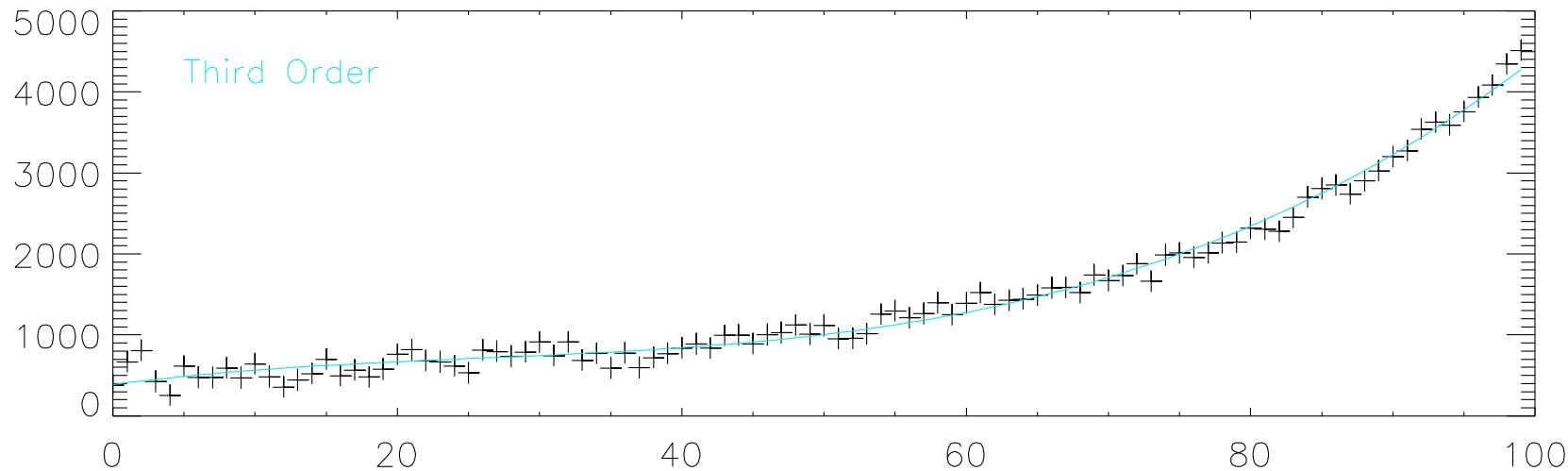
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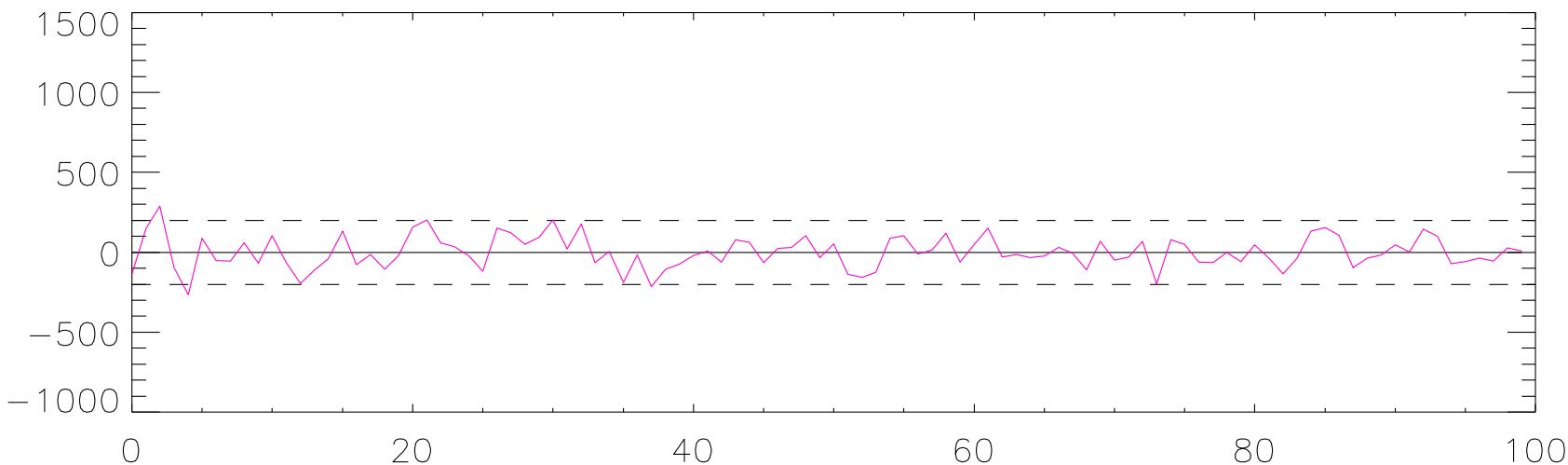
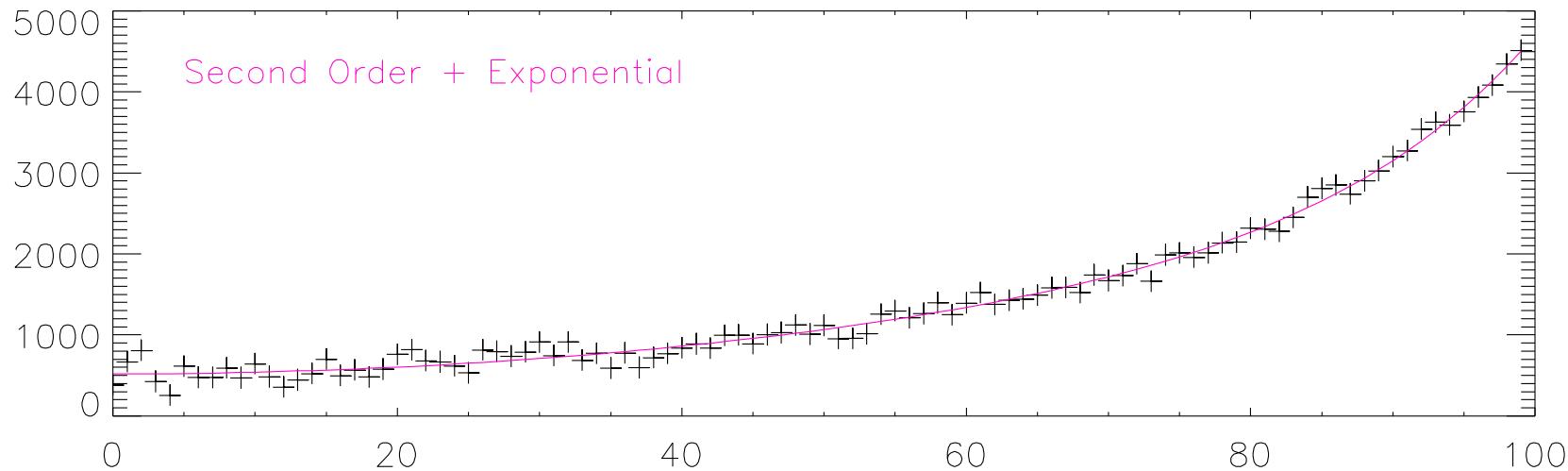
## 4: The SIR code

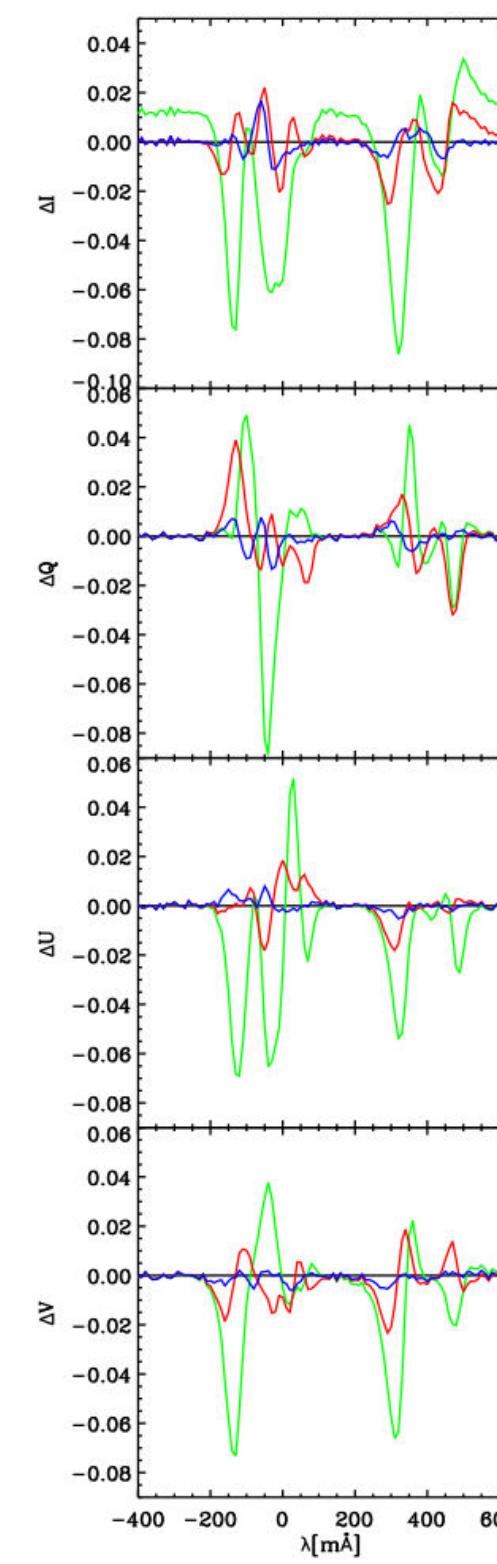
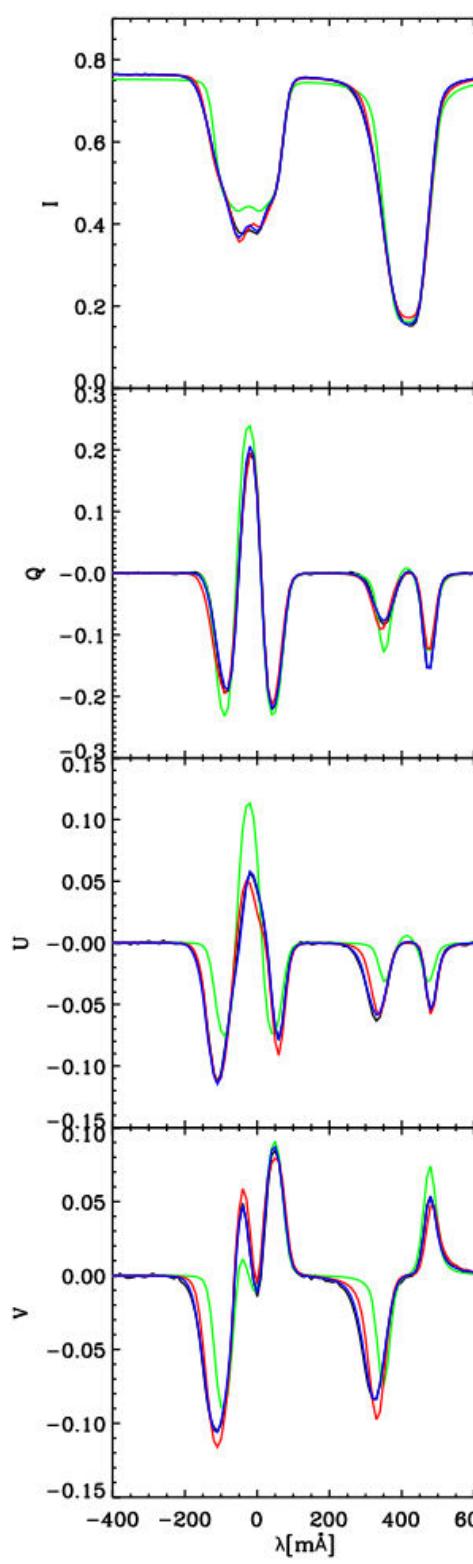
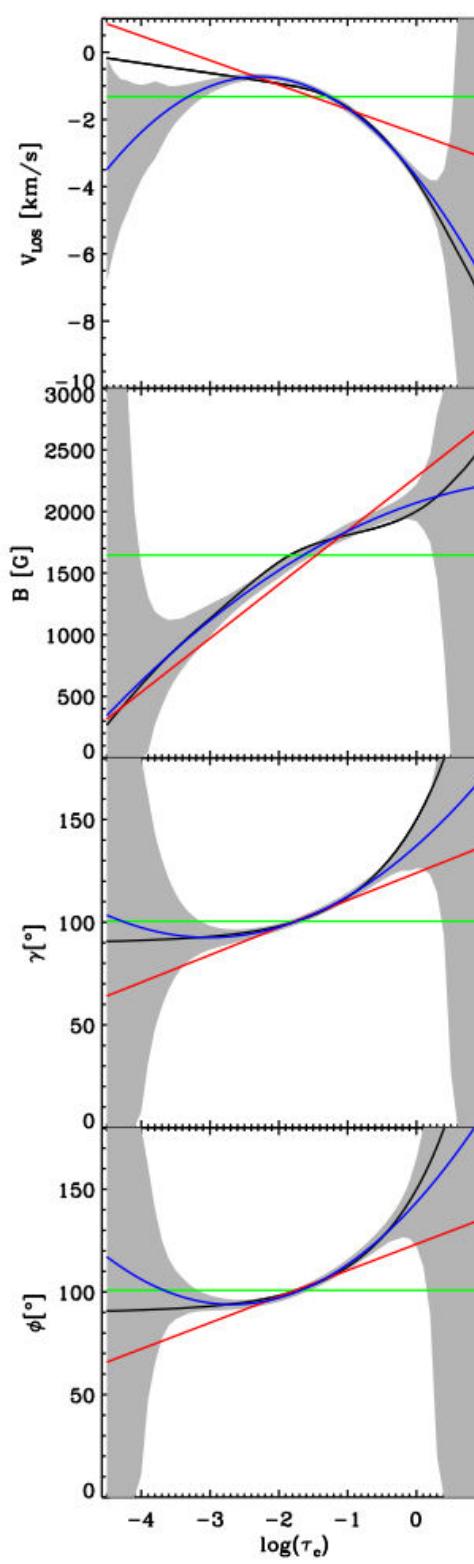
Unicity?



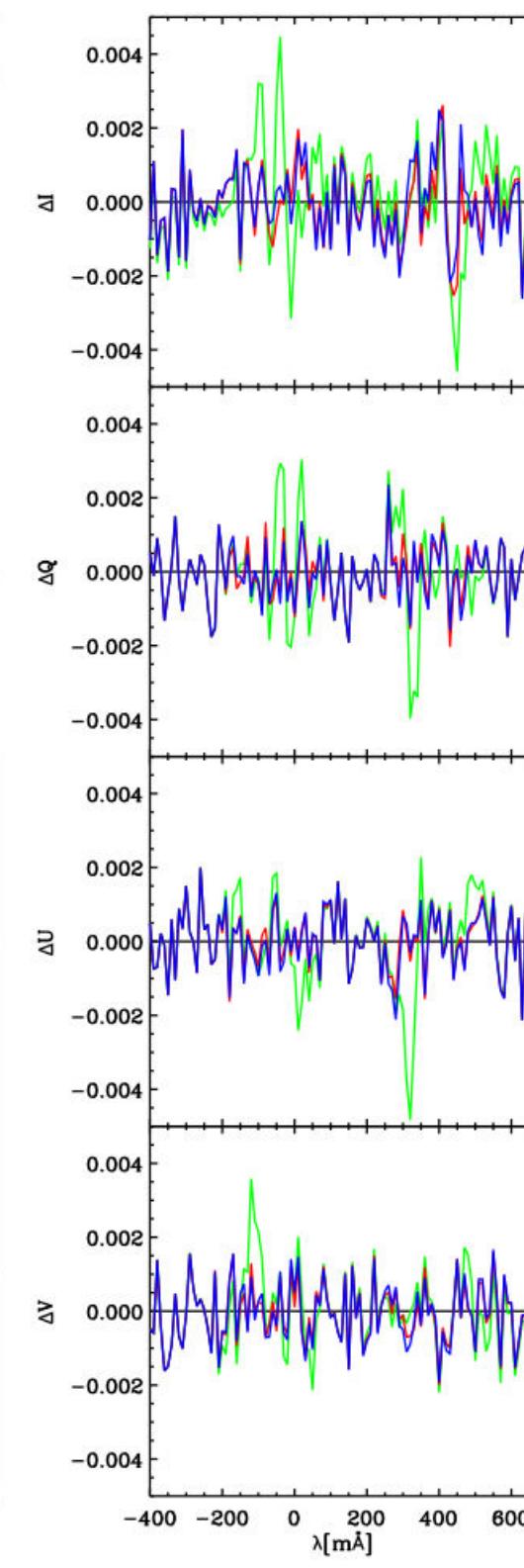
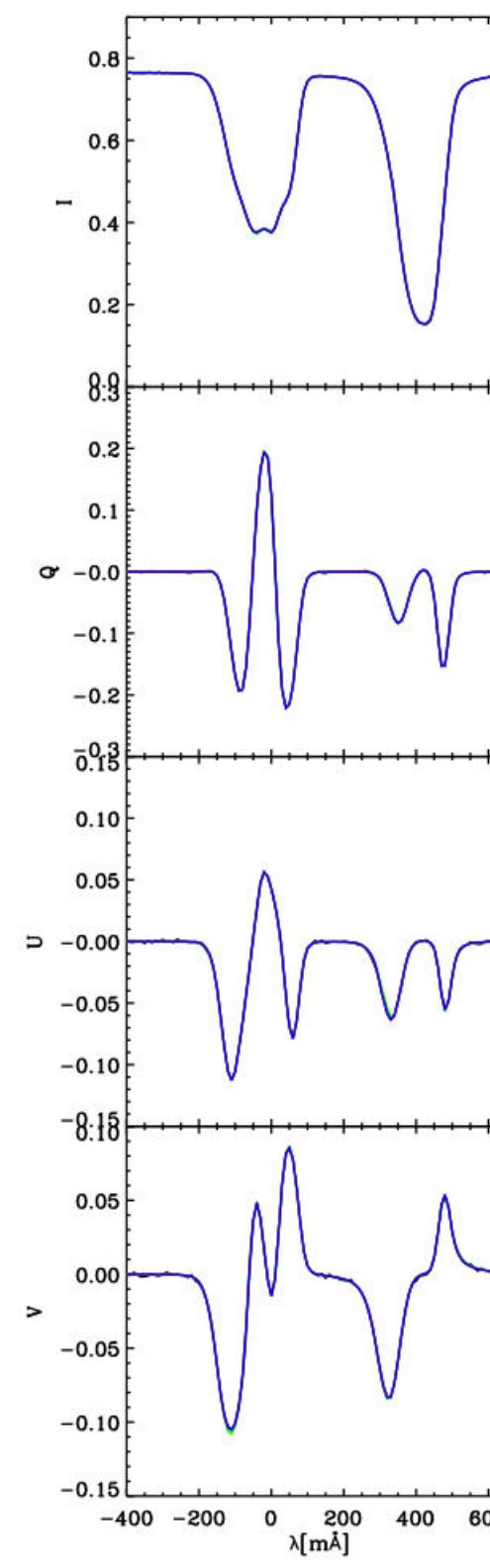
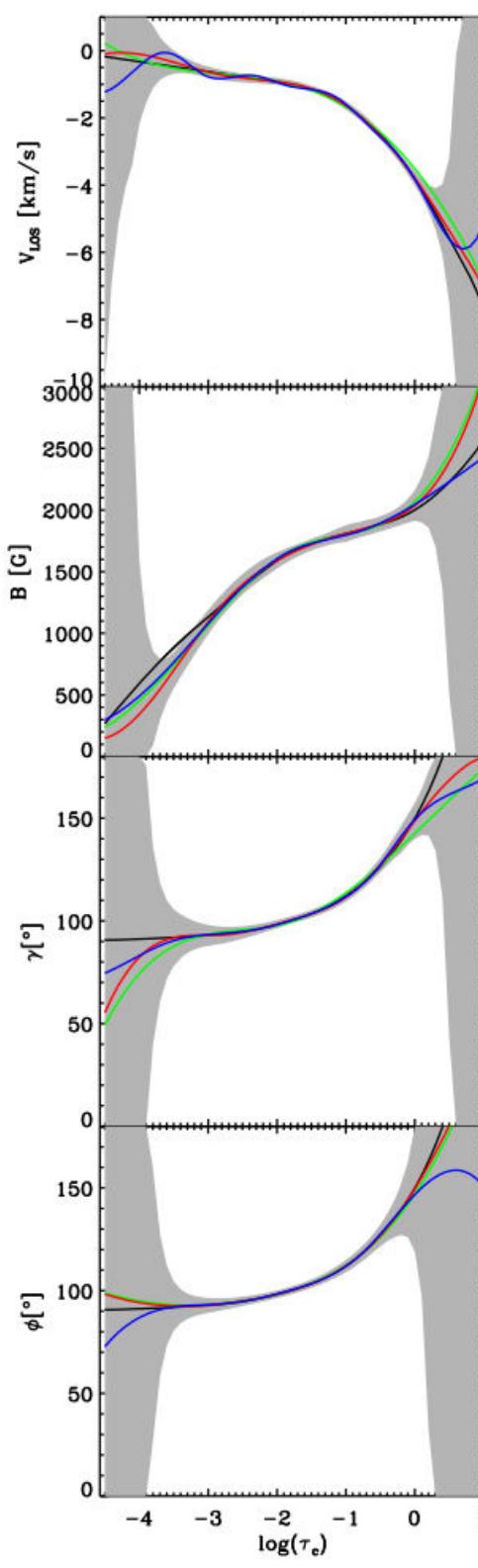
## 4: The SIR code

Unicity?





nodes( $T, B$ )	
2,1	Green line
4,2	Red line
6,3	Blue line
Observation	Black line



nodes(T, B)	
7,5	Green line
9,7	Red line
Automatic	Blue line
Observation	Black line

## 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) Living Reviews in Solar Physics, 13,4

## 5: How to choose an inversion technique?

### *Constant quantities*

KPNO	<a href="#">Harvey et al. (1972)</a>	LM	
HAO-KPNO	<a href="#">Auer et al. (1977)</a>	LM	
Florence	<a href="#">Landolfi et al. (1984)</a>	LM	✓
<u>HAO-ASP</u>	<a href="#">Skumanich et al. (1985)</a>	LM	✓
IAC MISMA	<a href="#">Sánchez Almeida (1997)</a>	LM	✓
CSIRO-Meudon	<a href="#">Rees et al. (2000)</a>	PCA	✓
<u>HAO MELANIE</u>	<a href="#">Socas-Navarro et al. (2001)</a>	LM	✓
HAO FATIMA	<a href="#">Socas-Navarro et al. (2001)</a>	PCA	✓
AIP ANN	<a href="#">Carroll and Staude (2001)</a>	ANN	
HAO He I D <sub>3</sub>	<a href="#">López Ariste and Casini (2003)</a>	PCA	✓
HAO ANN	<a href="#">Socas-Navarro (2003)</a>	ANN	
MPS HELIX	<a href="#">Lagg et al. (2004)</a>	GA	✓
IAC Molecular	<a href="#">Asensio Ramos (2004)</a>	LM	
IAA MILOS	<a href="#">Orozco Suárez and del Toro Iniesta (2007)</a>	LM	✓
<u>IAC HAZEL</u>	<a href="#">Asensio Ramos et al. (2008)</a>	LM	✓
HAO VFISV	<a href="#">Borrero et al. (2011)</a>	LM	✓
<u>IAC Sparse</u>	<a href="#">Asensio Ramos and de la Cruz Rodríguez (2015)</a>	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	<a href="#">Keller et al. (1990)</a>	LM	
IAC SIR	<a href="#">Ruiz Cobo and del Toro Iniesta (1992)</a>	LM	✓
ETH IT	<a href="#">Solanki et al. (1992b)</a>	LM	
IAC Flux tube	<a href="#">Bellot Rubio et al. (1997)</a>	LM	✓
<u>ETH SPINOR</u>	<a href="#">Frutiger and Solanki (1998)</a>	LM	✓
IAC NLTE	<a href="#">Socas-Navarro et al. (2000)</a>	LM	
HAO LILIA	<a href="#">Socas-Navarro (2001)</a>	LM	✓
<u>HAO-IAC NICOLE</u>	<a href="#">Socas-Navarro (2001)</a>	LM	✓
KIS SIRGAUS	<a href="#">Bellot Rubio (2003)</a>	LM	✓
IAA SIRJUMP	<a href="#">Louis et al. (2009)</a>	LM	✓
<u>IAC Bayes</u>	<a href="#">Asensio Ramos et al. (2009)</a>	B	✓
MPS Spatially coupled	<a href="#">van Noort (2012)</a>	LM	✓
IAC Regularization	<a href="#">Ruiz Cobo and Asensio Ramos (2013)</a>	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 have plenty of time or you are... a little crazy.)

# 5: How to choose an inversion technique?

## 1. ME family

- Advantages:
  - Fast (a typical map takes  $\sim$  hr).
  - Simple use & easy interpretation of results.
  - Robust & reliable.
  - HE, LTE etc approximations are not needed.
- 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 than ME inversions

## 5: How to choose an inversion technique?

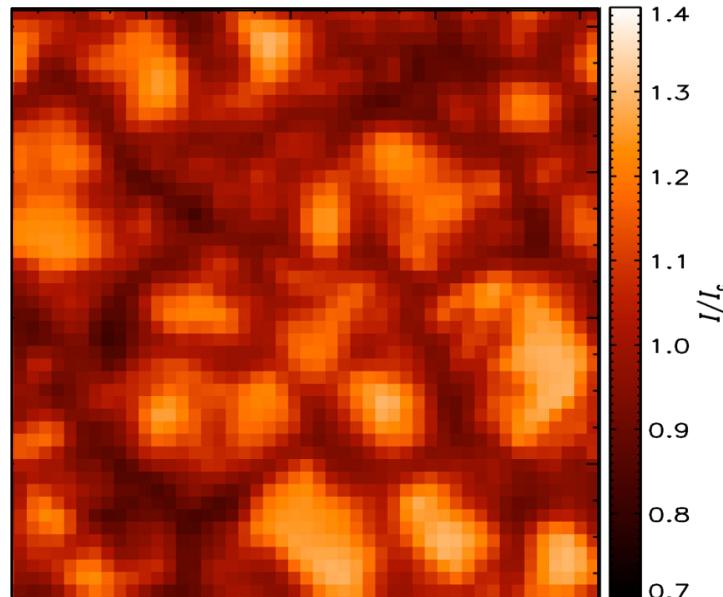
### Conclusions

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)

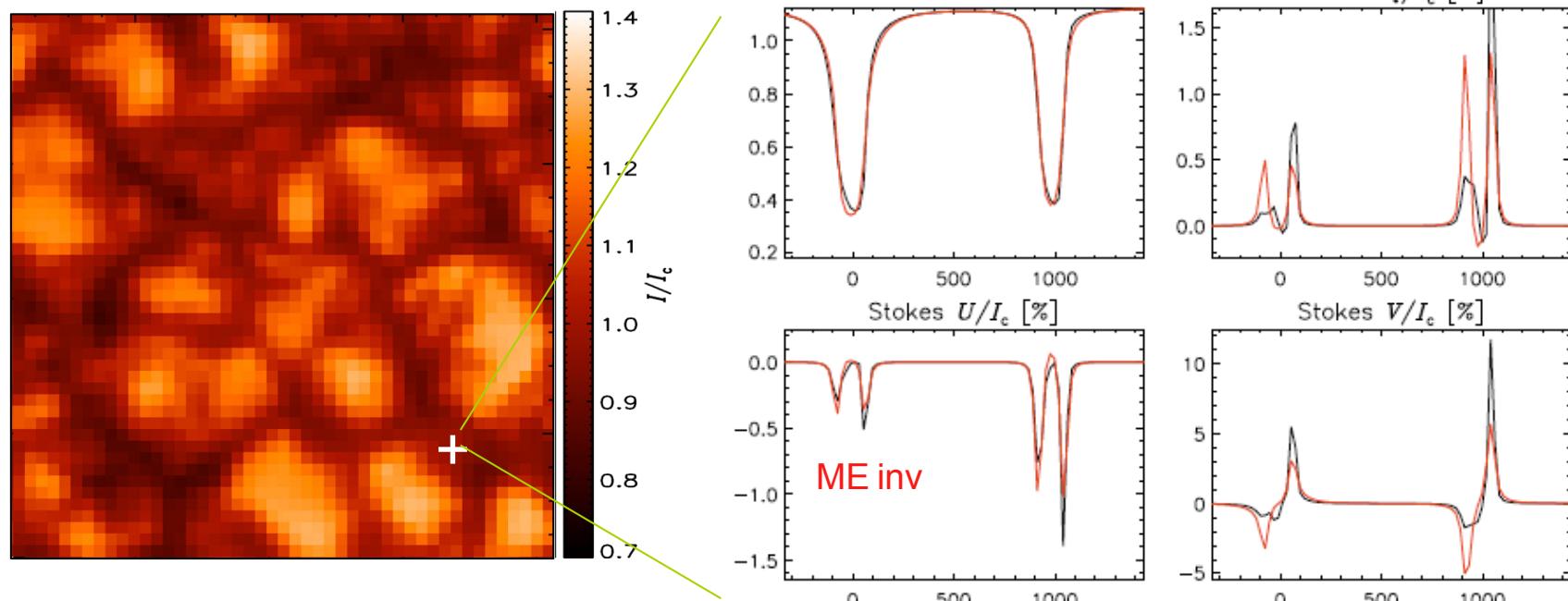


- Fe I 630.1 and 630.2 nm profiles degraded to Hinode/SP resolution and pixel size

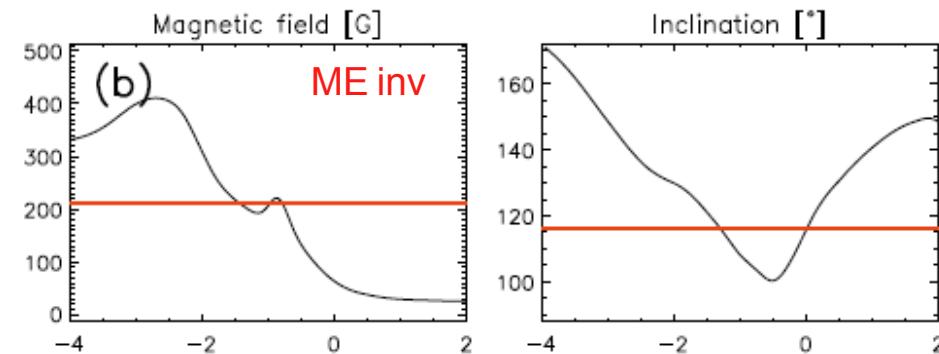
# 5: How to choose an inversion technique?

## ME inversions of high-spatial resolution profiles

MHD simulations (Vögler et al. 2005)



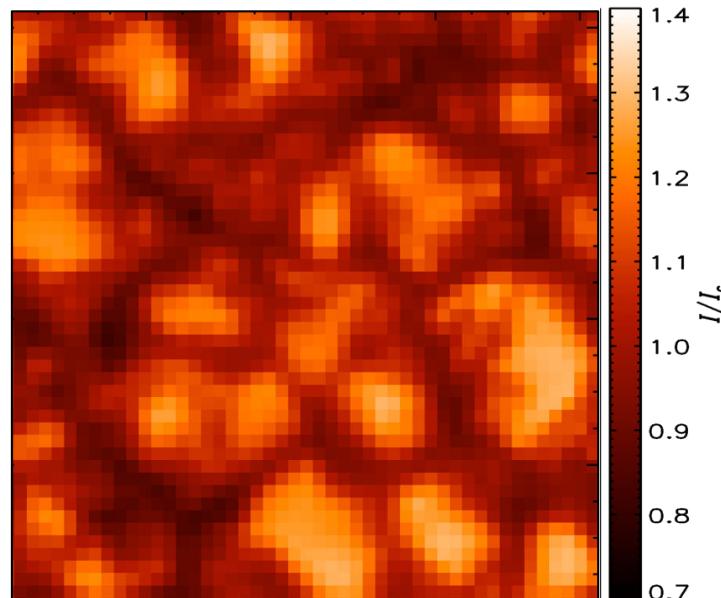
- Profiles reasonably well fitted
- ME results are some kind of “average” of physical parameters along the LOS



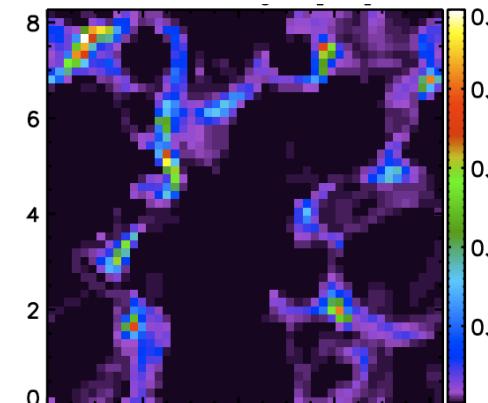
# 5: How to choose an inversion technique?

## ME inversions of high-spatial resolution profiles

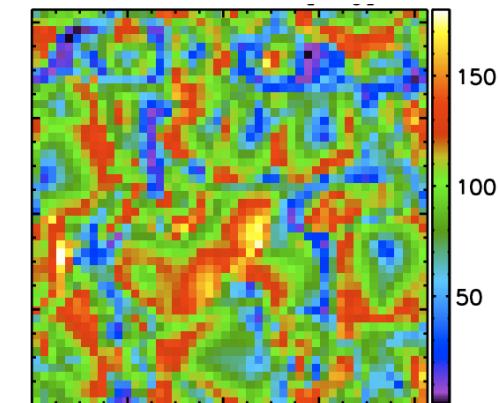
MHD simulations (Vögler et al. 2005)



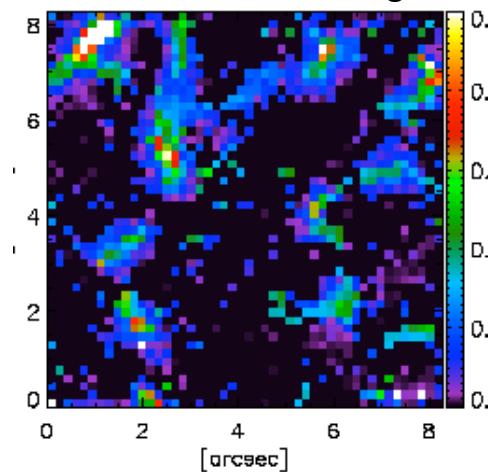
Magnetic field strength



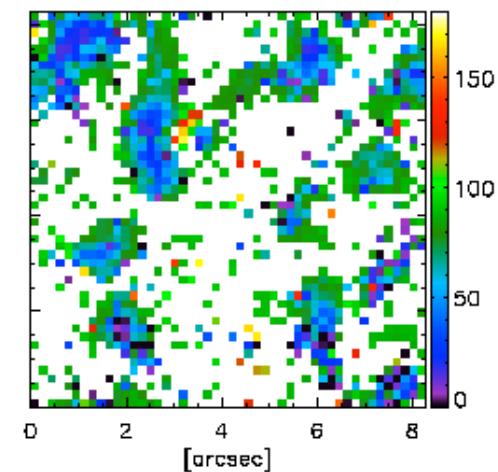
Field inclination



Inferred field strength



Inferred field inclination

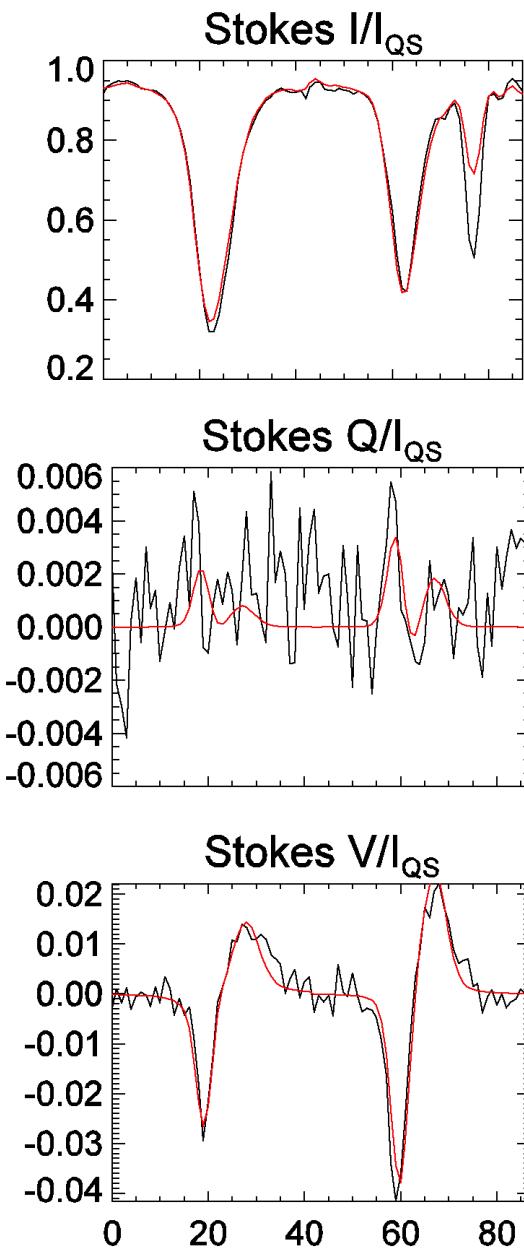
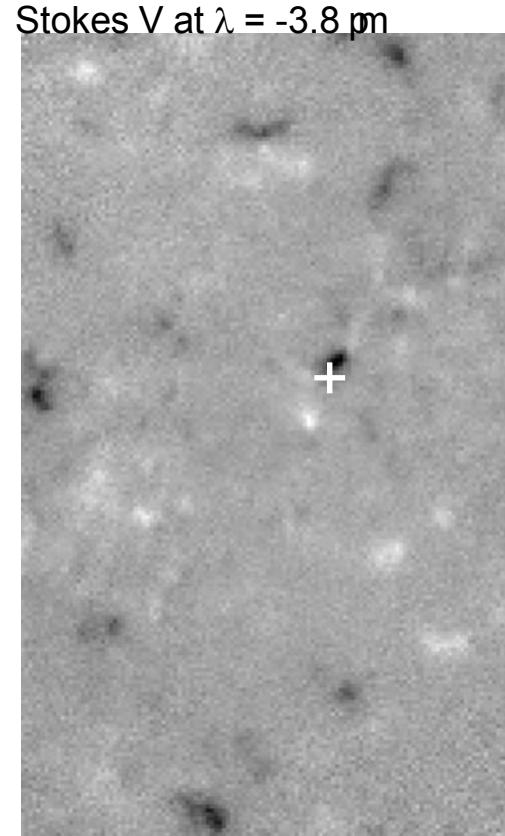
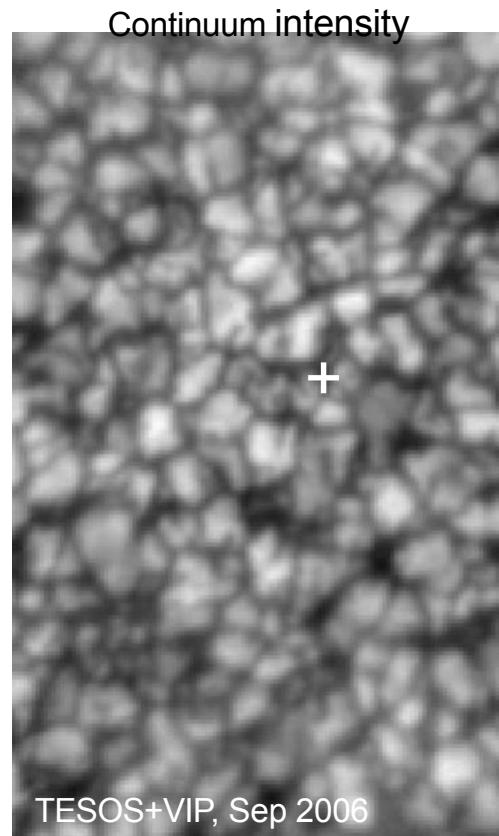


- Atmospheric parameters from MHD simulation at  $\log \tau = -2$
- Maps of inferred  $B$  and  $\gamma$  similar to real ones!

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

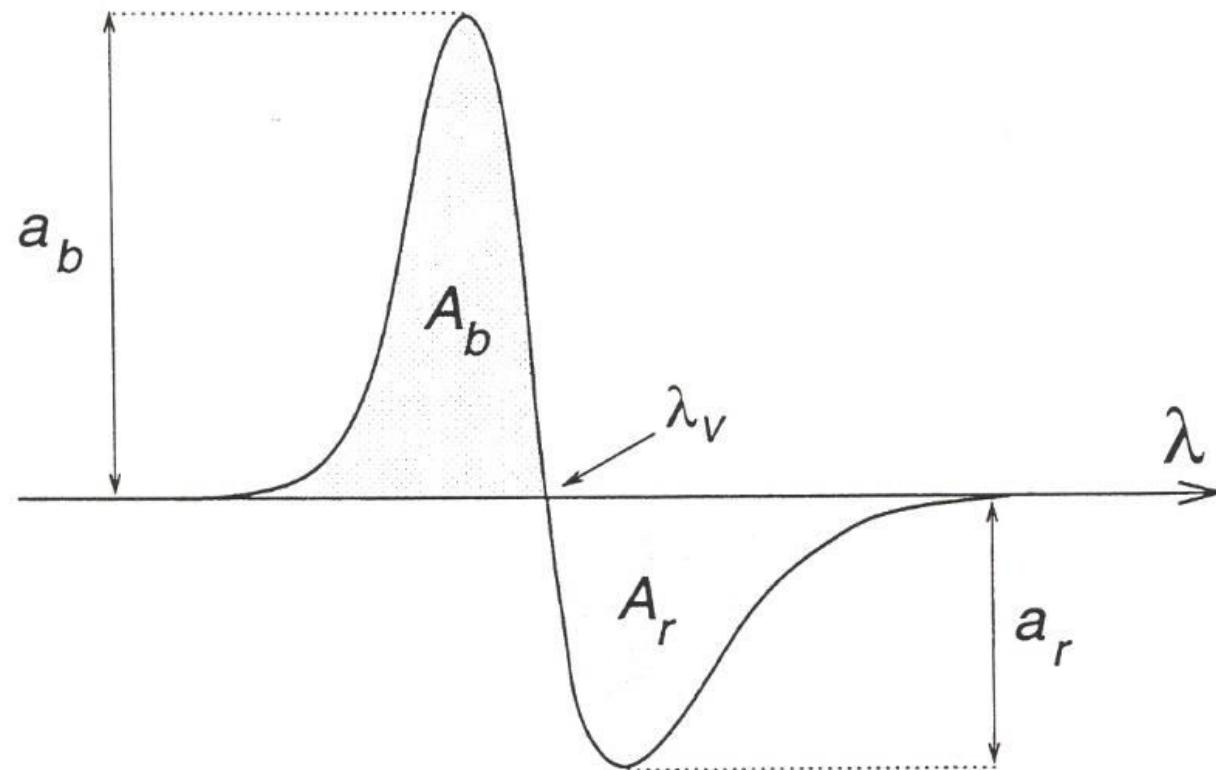
# 5: How to choose an inversion technique?

## Asymmetric Stokes profiles



- KIS/IAA Visible Imaging Polarimeter + TESOS + KAOS
- VTT, Observatorio del Teide
- **Spatial resolution:  $\sim 0.4''$**
- Quiet Sun at center, Fe I 630.15 and 630.25 nm

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



$$\delta a \equiv \frac{a_b - a_r}{a_b + a_r}, \quad \delta A \equiv \frac{A_b - A_r}{A_b + A_r},$$

# 5: How to choose an inversion technique?

## Asymmetric Stokes profiles

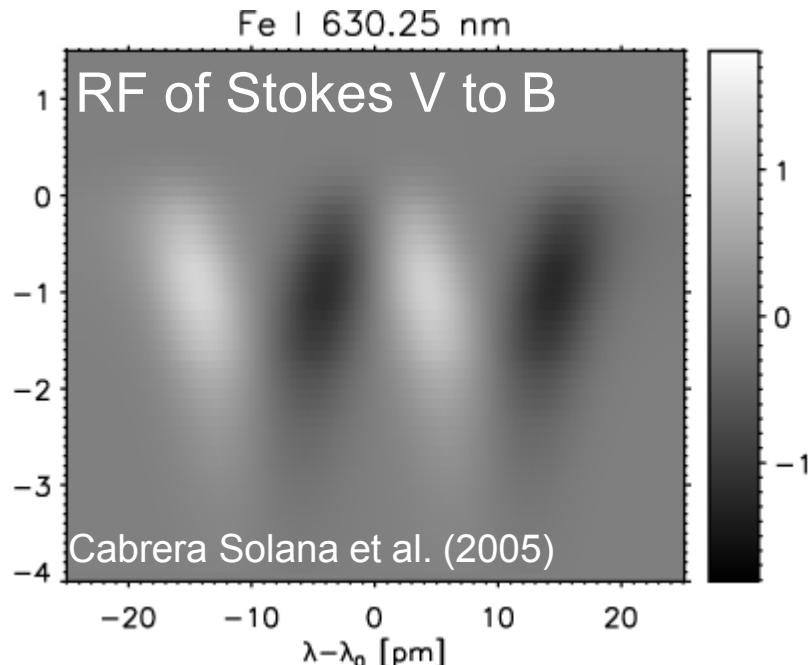
Amplitude asymmetry/  
Multi-lobed Stokes profiles

Area asymmetry

Different magnetic atmospheres  
coexisting in resolution element

Gradients/discontinuities of  $B$   
and  $v_{\text{LOS}}$  along LOS

Auer & Heasley (1978)



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

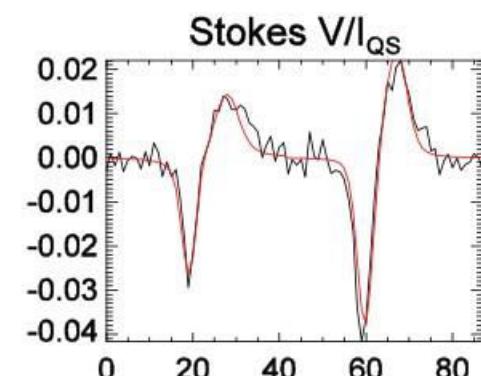
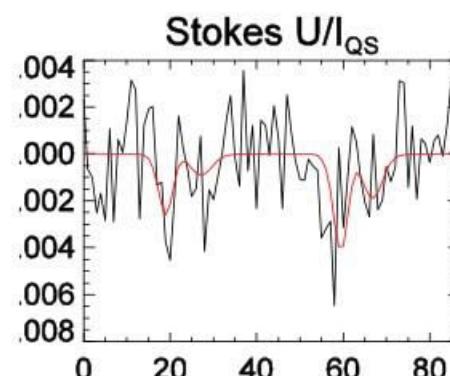
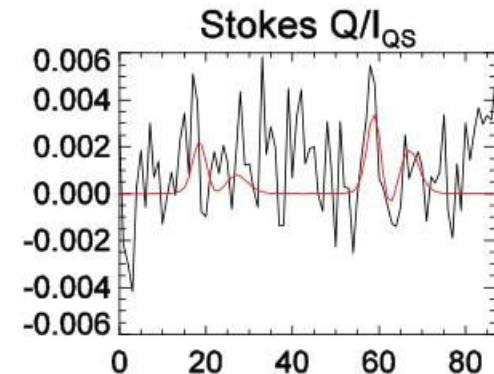
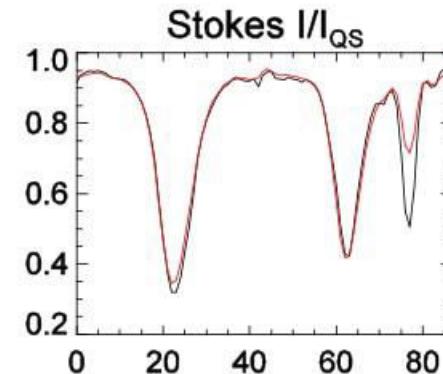
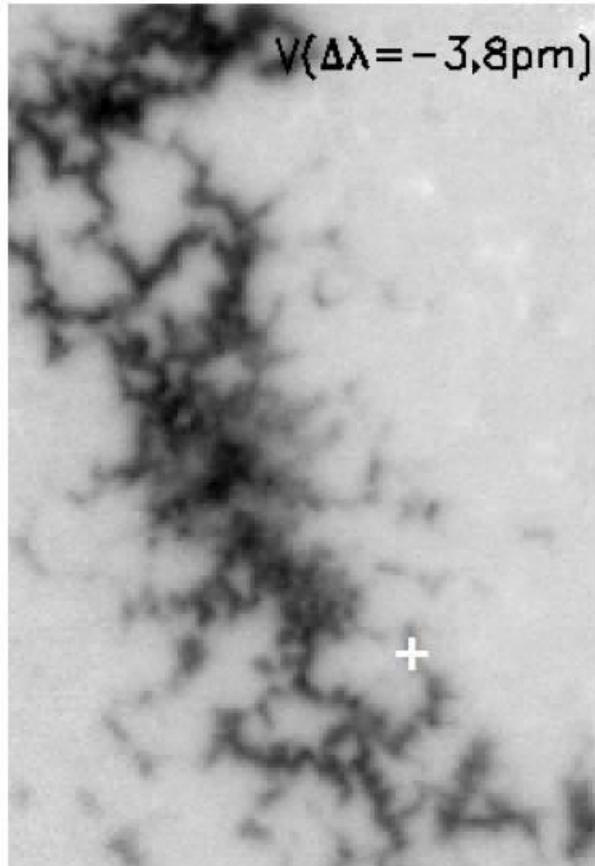
# 5: How to choose an inversion technique?

## Asymmetric Stokes profiles

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

# 5: How to choose an inversion technique?

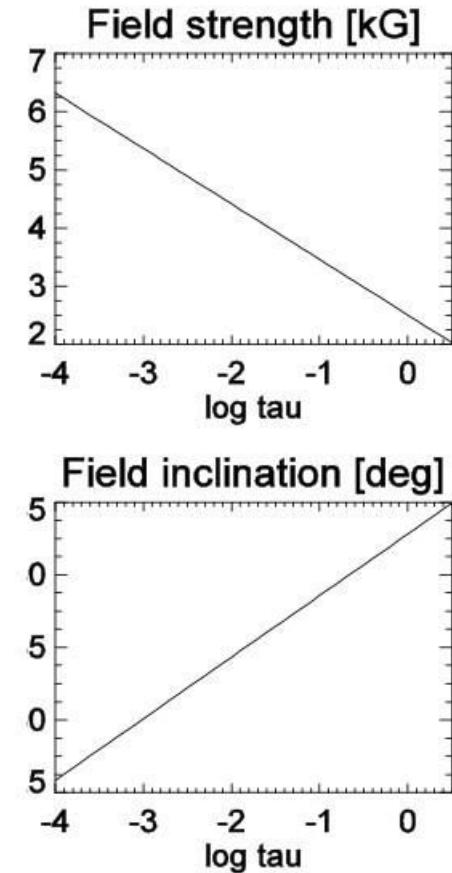
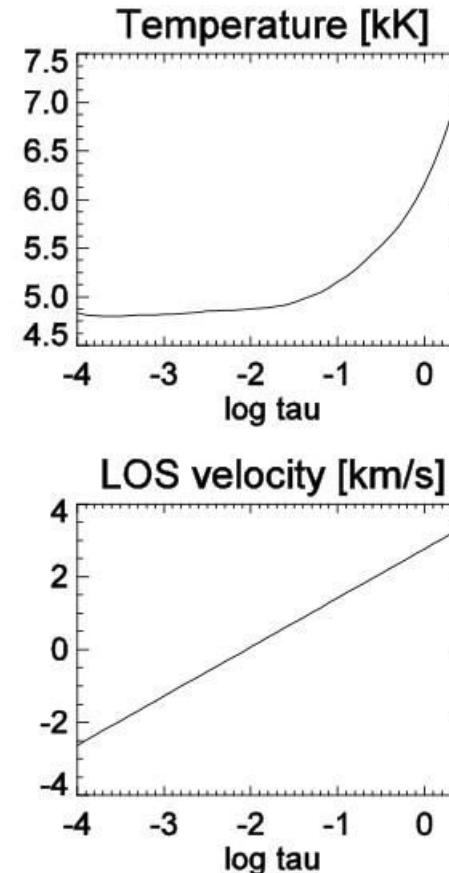
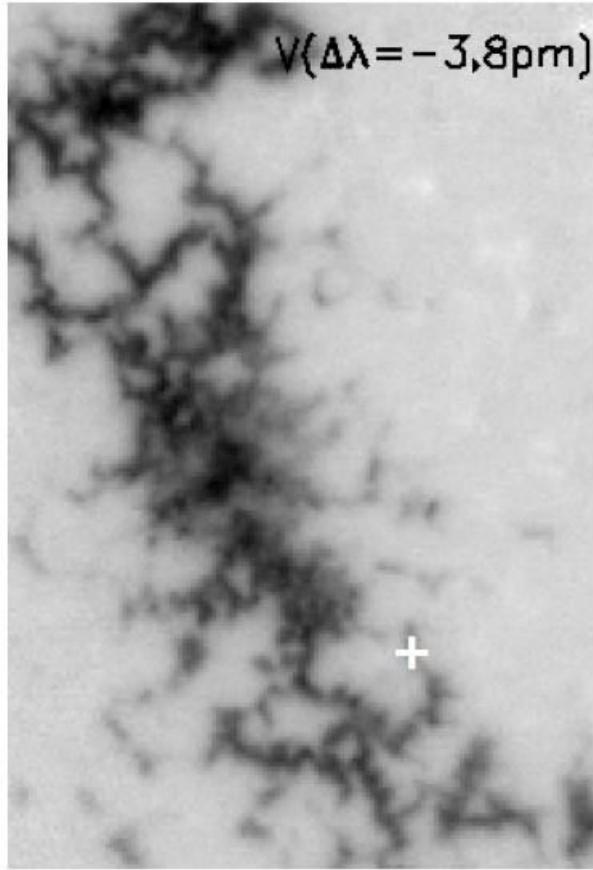
## Asymmetric Stokes profiles



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

# 5: How to choose an inversion technique?

## Asymmetric Stokes profiles

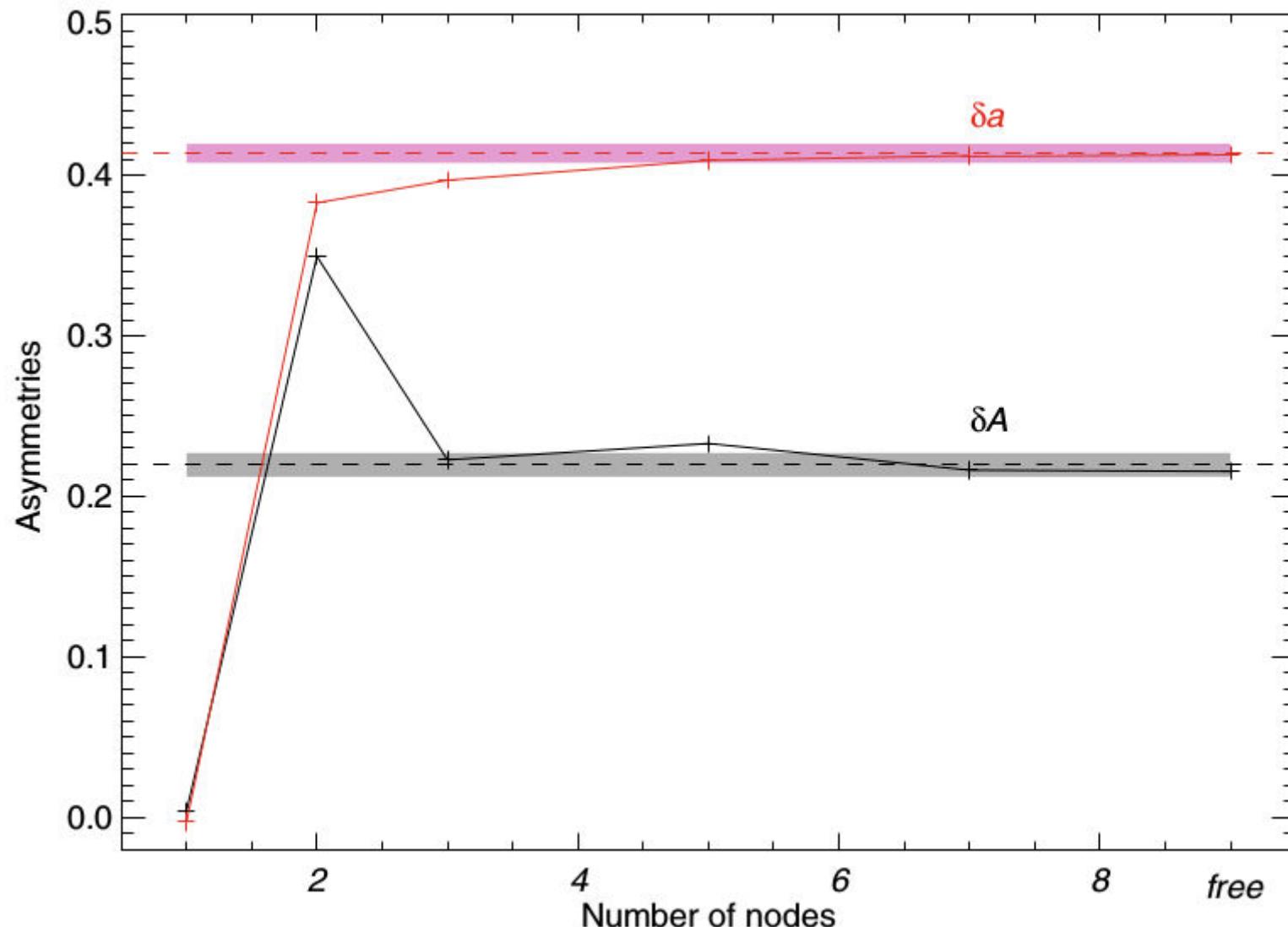


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## 5: How to choose an inversion technique?

### Asymmetric Stokes profiles

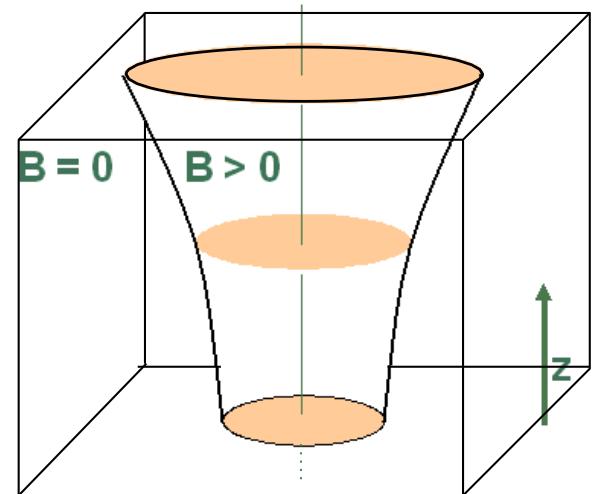
$$\delta a \equiv \frac{a_b - a_r}{a_b + a_r}, \quad \delta A \equiv \frac{A_b - A_r}{A_b + A_r},$$



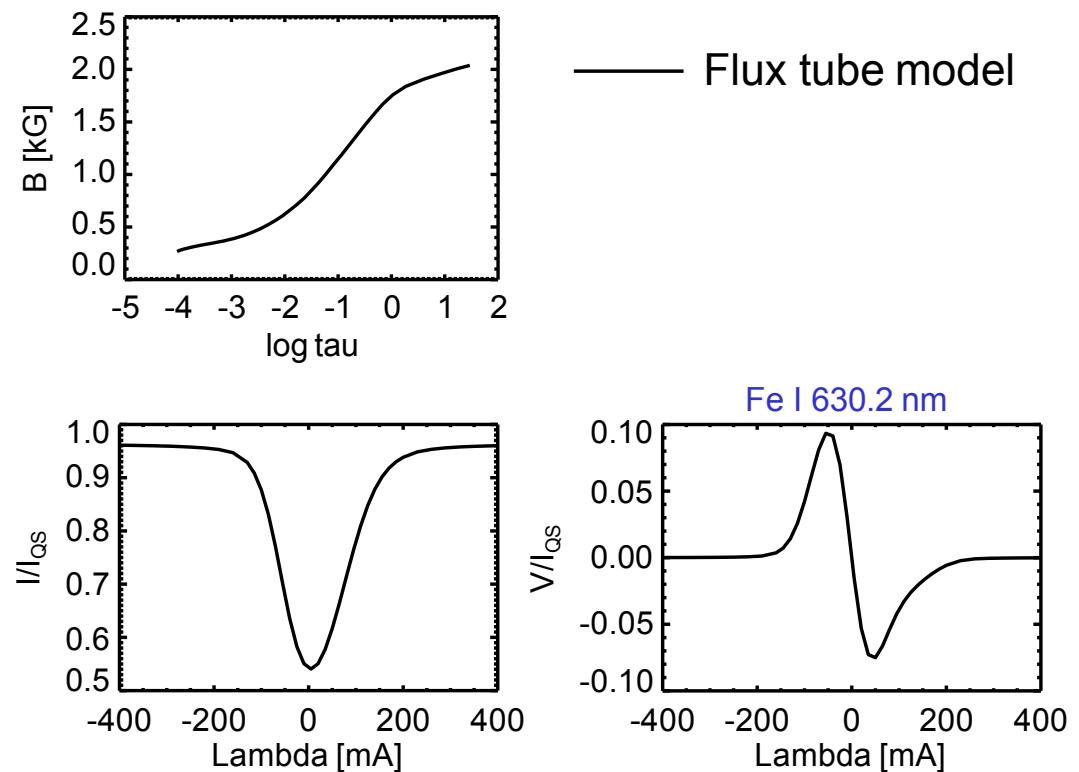
# 5: How to choose an inversion technique?

## 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!



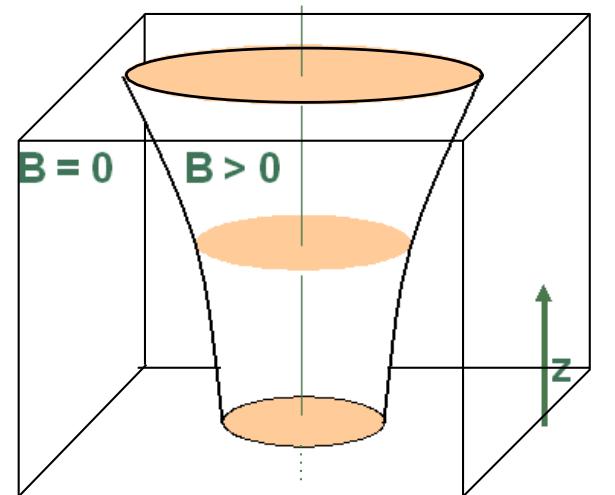
Magnetic flux tubes in facular regions



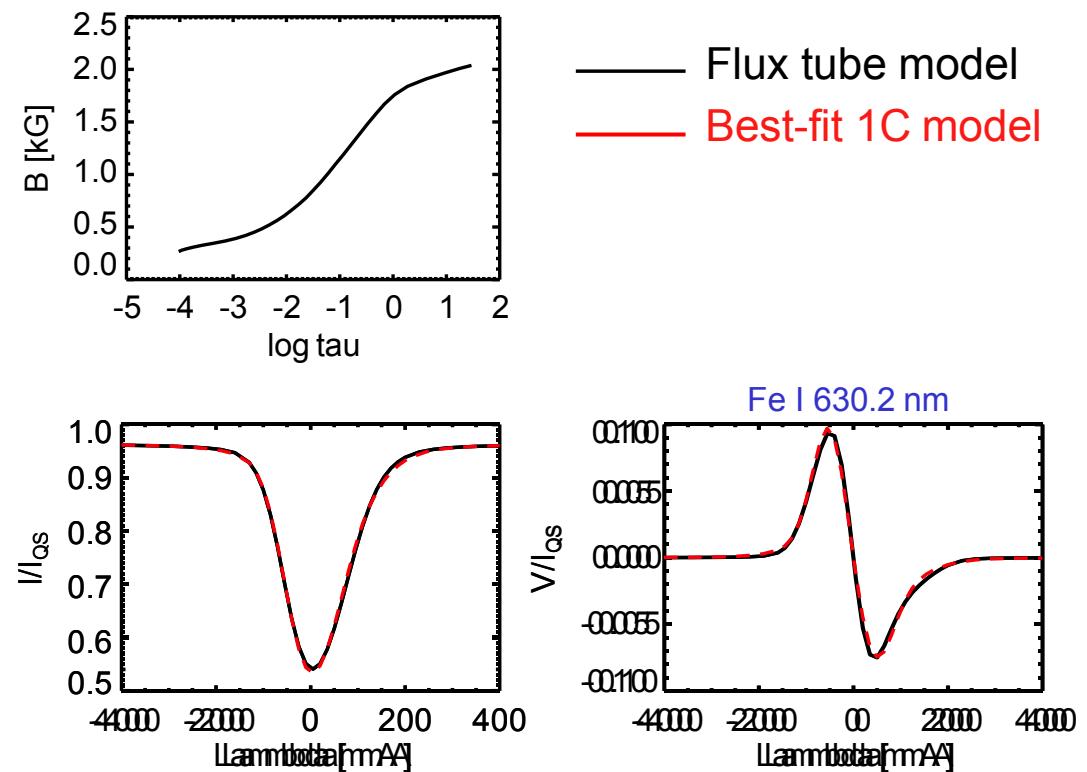
# 5: How to choose an inversion technique?

## Asymmetric Stokes profiles

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  - BUT: we get information about the magnetic structure of the atmosphere!



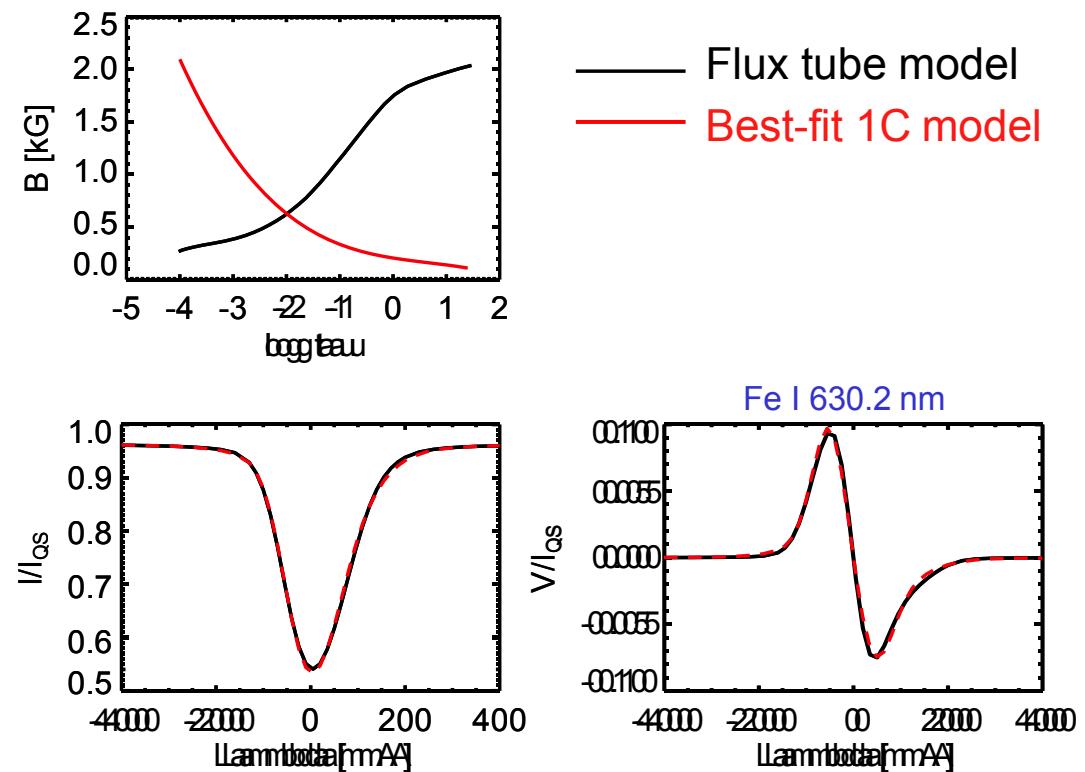
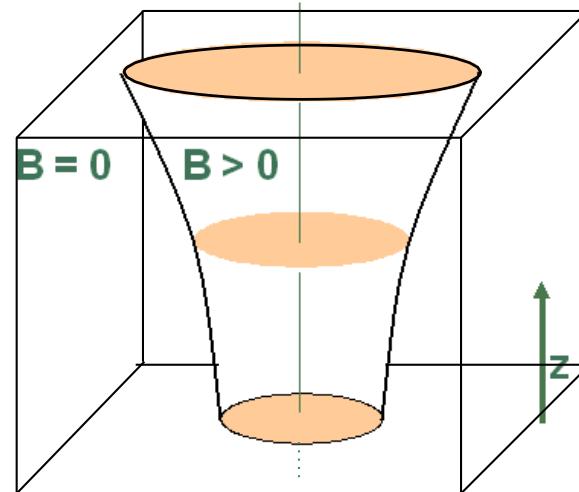
Magnetic flux tubes in facular regions



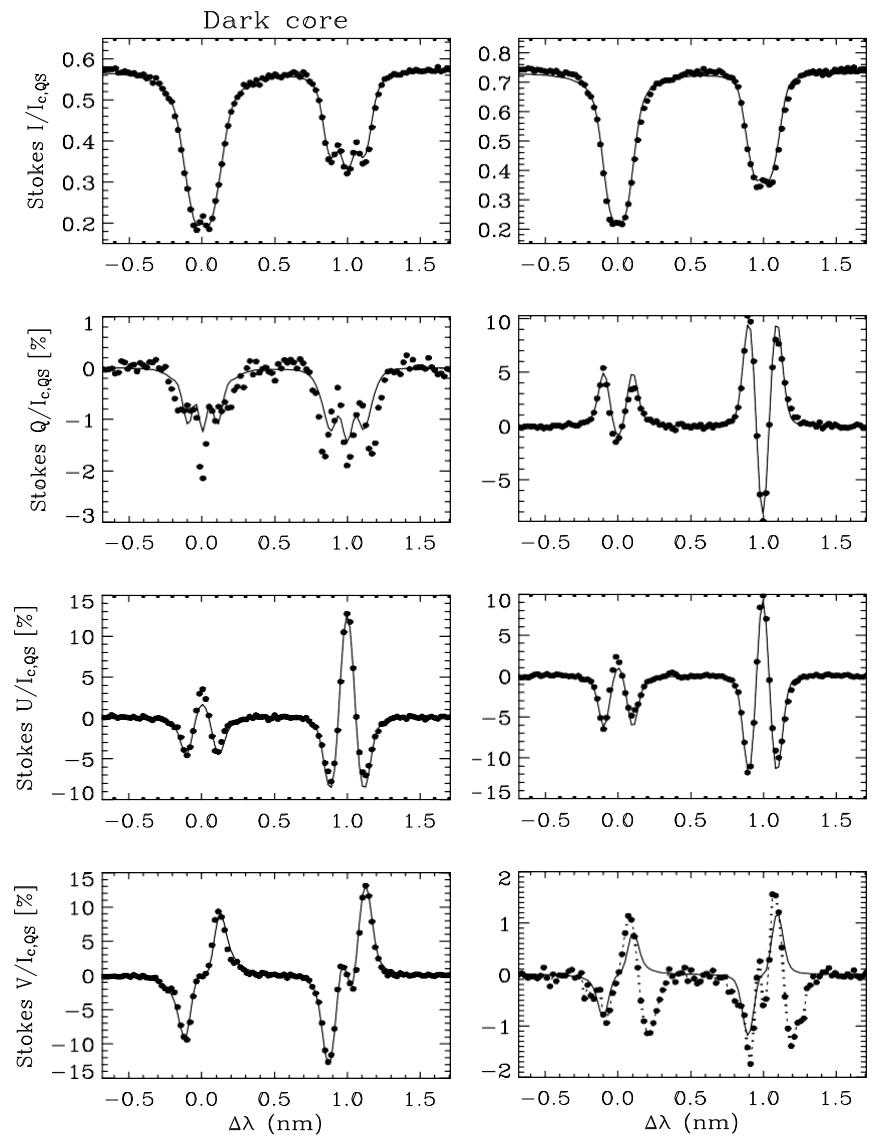
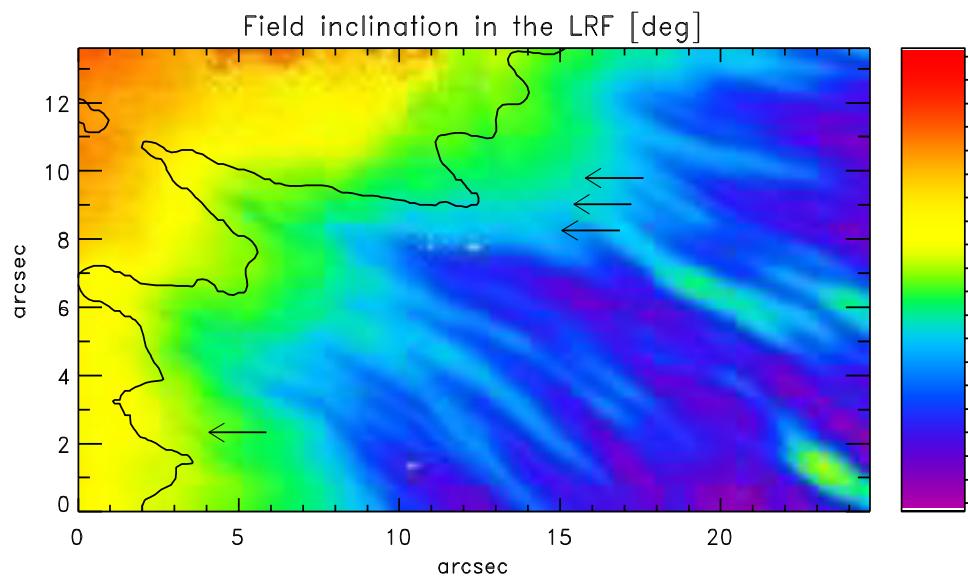
# 5: How to choose an inversion technique?

## 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!



# 1C SIR inversion of Hinode/SP data



## EXERCISE 2

Dark-cored penumbral filament

# Running SIR: input files

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

# 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     :
PSF file             :
Wavelength grid file (s) :mall.a.grid !
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? :1 ! (0 or blank=no, 1=yes)
Invert filling factor? :1 ! (0 or blank=no, 1=yes)
Invert stray light factor? :1 ! (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    :
Tolerance for SVD    :
Initial diagonal element :1 ! (DEFAULT value: 1.e-3)
Splines/Linear Interpolation :1 ! (0 or blank=splines, 1=linear)
Gas pressure at surface 1 :1 ! (0 or blank=Pe boundary cond.)
Gas pressure at surface 2 :1 ! (0 or blank=Pe boundary cond.)
Magnetic pressure term? :0 ! (0 or blank=no, 1=yes)
NLTE Departures filename :1 ! 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          ! (=synthesis)
Observed profiles     (*):perfil.per !
Stray light file      :
PSF file              :
Wavelength grid file  (s):mallag.grid !
Atomic parameters file :LINES        !
Abundances file       :THEVENIN    !
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?:1          ! (0 or blank=no, 1=yes)
Invert filling factor?:1            ! (0 or blank=no, 1=yes)
Invert stray light factor?:1          ! (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     :
Tolerance for SVD      :
Initial diagonal element:
Splines/Linear Interpolation:
Gas pressure at surface 1:
Gas pressure at surface 2:
Magnetic pressure term?:0          ! (0 or blank=no, 1=yes)
NLTE Departures filename:
--:** sir.trol          (Text Fill)--L1--C0--Top--
```

Profile file: [ ].per

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	-0.00174846		
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		

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          ! (=synthesis)
Observed profiles     (*):perfil.per !
Stray light file      :
PSF file               :
Wavelength grid file  (s):mallag.grid !
Atomic parameters file :LINES        !
Abundances file       :THEVENIN    !
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? :
Invert filling factor? :
Invert stray light factor? :
mu=cos (theta)        :0.64
Estimated S/N for I    :200
Continuum contrast      :
Tolerance for SVD      :
Initial diagonal element :
Splines/Linear Interpolation :
Gas pressure at surface 1 :
Gas pressure at surface 2 :
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

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					
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.					
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	

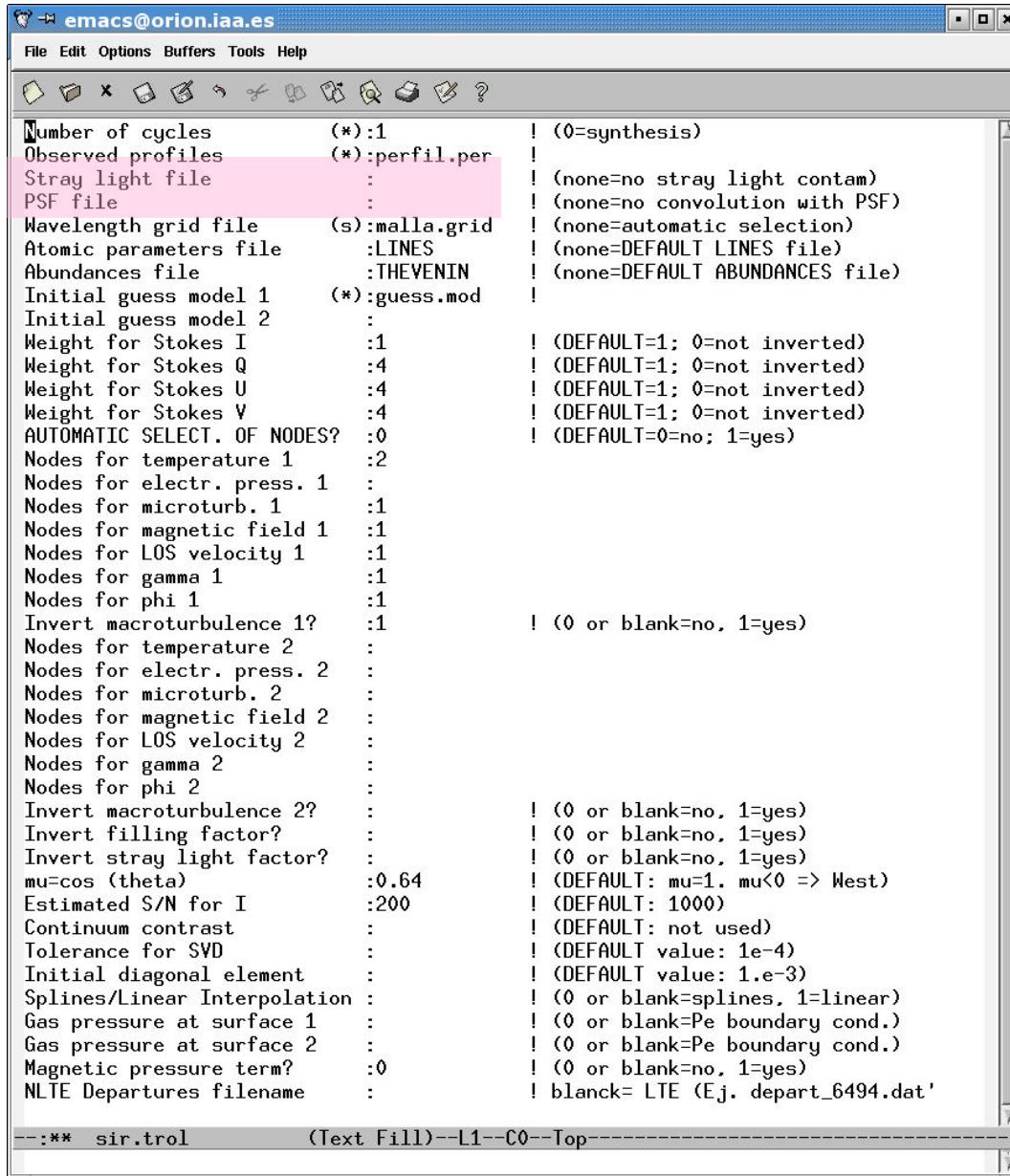
Line  $\Delta\lambda$   $I/I_{qs}$   $Q/I_{qs}$   $U/I_{qs}$   $V/I_{qs}$   
index [mA]

read\_profiles.pro  
write\_profiles.pro

Basilio Ruiz Cobo

# Running SIR: input files

All the program is control by a **control file**:



The screenshot shows an Emacs window titled "emacs@orion.iaa.es" displaying a configuration file named "sir.trol". The file contains numerous parameters and their values, many of which are preceded by a double asterisk (\*) indicating they are optional. The parameters include:

- 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):mall.a.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:  $\mu=1$ .  $\mu<0 \Rightarrow$  West)
- Estimated S/N for I :200 ! (DEFAULT: 1000)
- Continuum contrast :
- Tolerance for SVD :
- Initial diagonal element :
- Splines/Linear Interpolation :
- Gas pressure at surface 1 :
- Gas pressure at surface 2 :
- 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

PSF file: a two column file containing, wavelength, and the PSF

# Stray-light considerations

- Stray-light in 1C inversions:
  - $I_{\text{obs}} = (1-\alpha) I_1 + \alpha I_{\text{stray}}$
  - 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  $f$
  - $I_{\text{obs}} = (1-\alpha) [f I_1 + (1-f) I_2] + \alpha I_{\text{stray}}$
- 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

```
emacs@orion.iaa.es
File Edit Options Buffers Tools Help
Number of cycles      (*):1          ! (0=synthesis)
Observed profiles     (*):perfil.per !
Stray light file      :
PSF file              :
Wavelength grid file  (s):mallag.grid !
Atomic parameters file :LINES        !
Abundances file       :THEVENIN    !
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? :
Invert filling factor? :
Invert stray light factor? :
mu=cos (theta)        :0.64        ! (0 or blank=no, 1=yes)
Estimated S/N for I    :200         ! (DEFAULT: mu=1. mu<0 => West)
Continuum contrast      :
Tolerance for SVD      :
Initial diagonal element :
Splines/Linear Interpolation :
Gas pressure at surface 1 :
Gas pressure at surface 2 :
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

```
emacs@dhcp-200-191.mtk.nao.ac.jp
File Edit Options Buffers Tools Help
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--
```

# 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      :
PSF file              :
Wavelength grid file  (s):mallag.grid
Atomic parameters file :LINES        !
Abundances file       :THEVENIN    !
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      :
Tolerance for SVD      :
Initial diagonal element:
Splines/Linear Interpolation:
Gas pressure at surface 1:
Gas pressure at surface 2:
Magnetic pressure term? :0          ! (0 or blank=no, 1=yes)
NLTE Departures filename:          ! blank= LTE (E.g. depart_6494.dat'

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

## ATOMIC PARAMETER FILE

emacs@orion.iaa.es

File Edit Options Buffers Tools Help

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

Line index

Atom Ion  $\lambda$  E

$\chi$  log gf transition Barklem's coeff.

Line index	Atom Ion $\lambda$	E	$\chi$	log gf	transition	Barklem's coeff.
1	1=FE 1 6301.5012	1.0	3.654	-0.75	5P 2.0-	5D 2.0 0.243 2.3520e-14
2	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--

# Running SIR: input files

emacs@orion.iaa.es

File Edit Options Buffers Tools Help

Number of cycles (\*):1  
 Observed profiles (\*):perfil.per  
 Stray light file :  
 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--:\*\* sir.trol (Text Fill)

Vmac  
 f=Fillig factor  
 $\alpha$ = Stray light factor

Model file [ ].mod

emacs@orion.iaa.es

File Edit Options Buffers Tools Help

	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

log  $\tau$  T  $P_e$   $v_{mic}$  B  $v_{LOS}$   $\gamma$   $\varphi$  z [km]  $P_g$   $\rho$

# Running SIR: input files

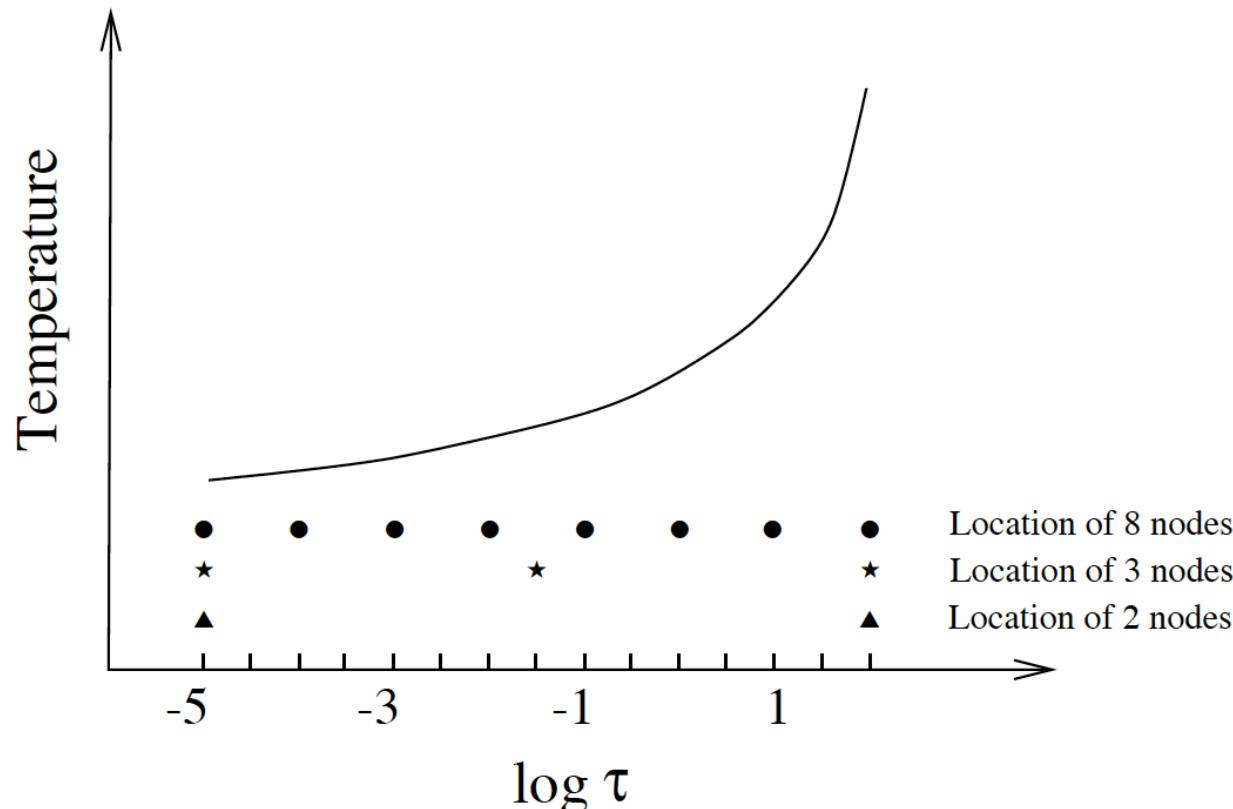
The screenshot shows an Emacs window titled "emacs@orion.iaa.es" displaying an SIR input file. The file contains numerous configuration parameters, many of which are highlighted with a pink background. The parameters include:

- Number of cycles :1 ! (0=synthesis)
- Observed profiles :perf1.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?:1 ! (0 or blank=no, 1=yes)
- Invert filling factor?:1 ! (0 or blank=no, 1=yes)
- Invert stray light factor?:1 ! (0 or blank=no, 1=yes)
- $\mu=\cos(\theta)$ :0.64 ! (DEFAULT:  $\mu=1$ .  $\mu<0 \Rightarrow$  West)
- Estimated S/N for I :200 ! (DEFAULT: 1000)
- Continuum contrast :
- Tolerance for SVD : ! (DEFAULT value:  $1e-4$ )
- Initial diagonal element : ! (DEFAULT value:  $1.e-3$ )
- Splines/Linear Interpolation :
- 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      :
PSF file               :
Wavelength grid file  (s):mallagrid  !
Atomic parameters file :LINES        !
Abundances file       :THEVENIN    !
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)
Weight for Stokes V   :4           ! (DEFAULT=0=no; 1=yes)
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 for LOS velocity 1 :1
Nodes for gamma 1      :1
Nodes for phi 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?: 1           ! (0 or blank=no, 1=yes)
Invert filling factor?: 1           ! (0 or blank=no, 1=yes)
Invert stray light factor?: 1           ! (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      :
Tolerance for SVD      :
Initial diagonal element:
Splines/Linear Interpolation:
Gas pressure at surface 1:
Gas pressure at surface 2:
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 than the specified
- Number of nodes \* means any value (only for authomatic selection)

# Running SIR: input files

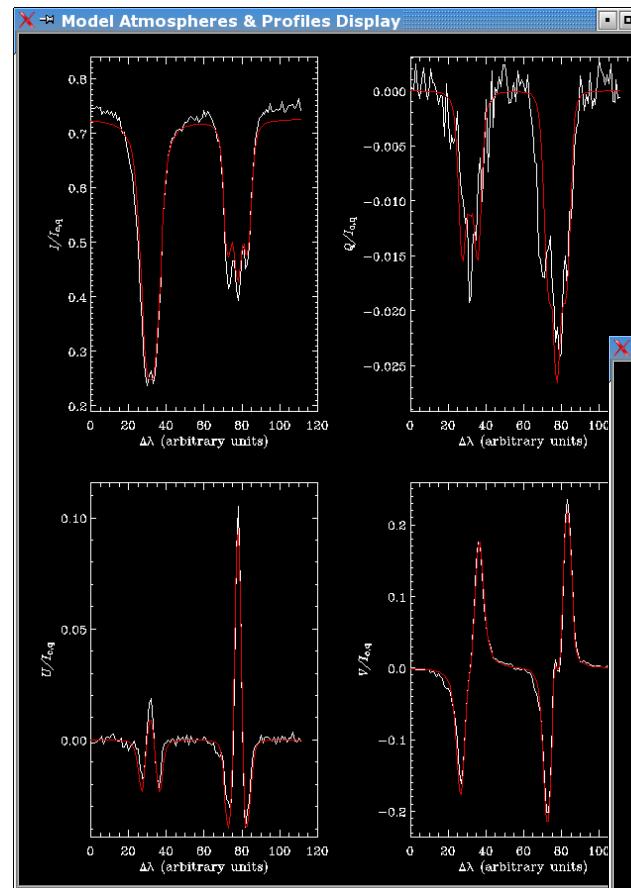
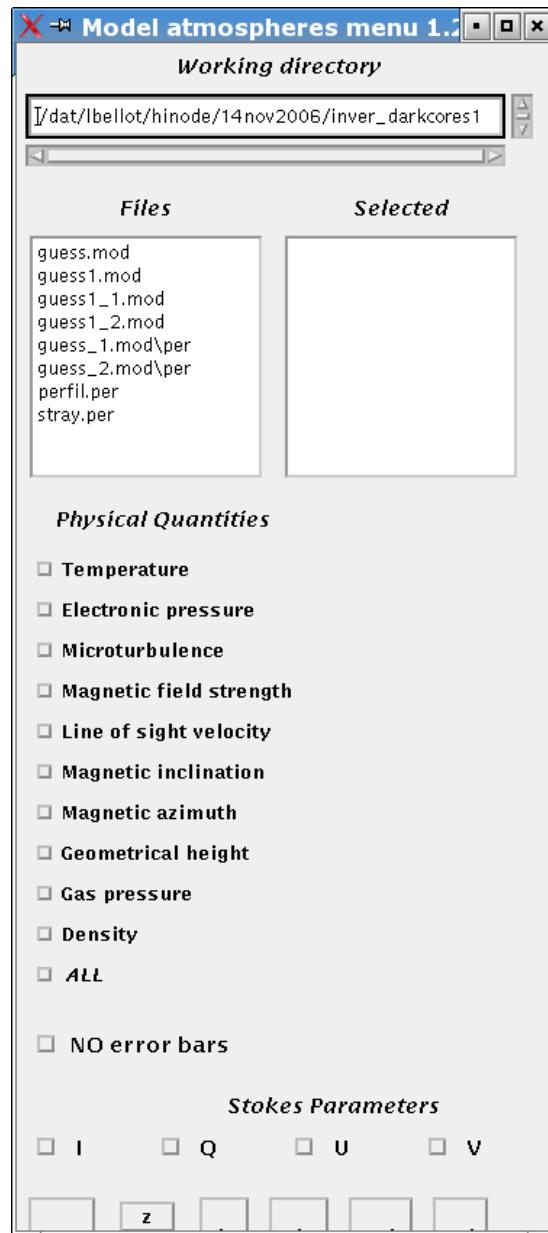
The screenshot shows an Emacs window titled "emacs@orion.iaa.es" displaying an SIR input file. The file contains various parameters and their values, many of which have comments explaining their meaning. A pink rectangular highlight covers the bottom portion of the file, starting from the parameter "mu=cos(theta)" and ending at "NLTE Departures filename".

```
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):mallag.grid !
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?:1          ! (0 or blank=no, 1=yes)
Invert filling factor?:1            ! (0 or blank=no, 1=yes)
Invert stray light factor?:1        ! (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--
```

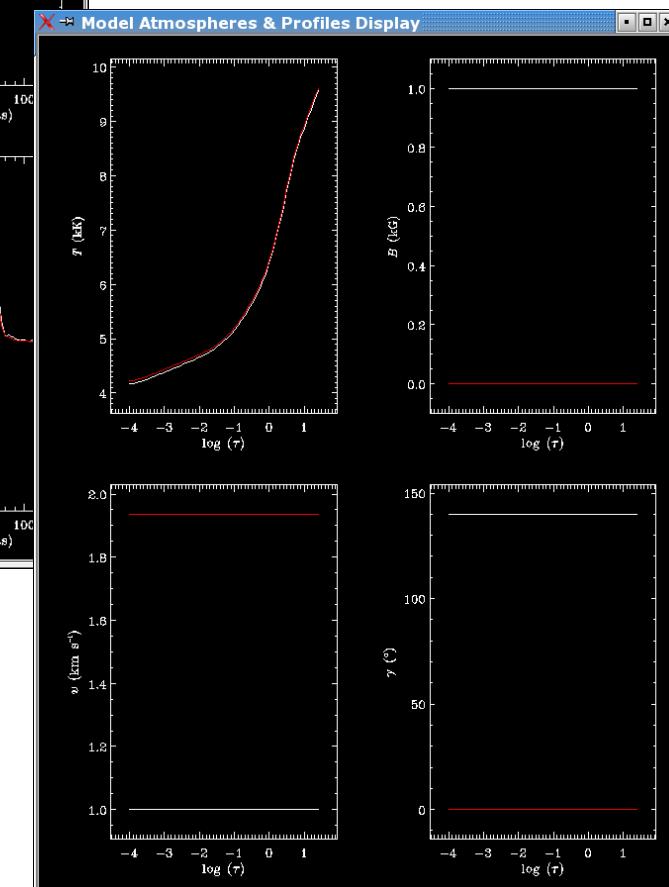
# Executing the inversion

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

# Visualizing SIR results: graphics2.pro



Stokes profiles



Model atmospheres

# 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  $v_{\text{LOS}}$  (e.g., 1 kG, 60°, 2 km/s)
  2. constant  $v_{\text{LOS}}$ , gradients of  $B$  and inclination
  3. gradients of  $B$ , inclination and  $v_{\text{LOS}}$
- Invert profiles from (3.), starting from initial guess model with flat stratifications of  $B$ ,  $v_{\text{LOS}}$ , and inclination (modify hsra11.mod)
  - 1 node in  $B$ ,  $v_{\text{LOS}}$ , inclination
  - 2 nodes in  $B$ , and  $v_{\text{LOS}}$  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  $v_{\text{LOS}}$ ?
  4. What happens with 10 nodes in B and  $v_{\text{LOS}}$ ?
- Invert profiles from (3.), starting from initial guess model with flat stratifications of B,  $v_{\text{LOS}}$ , and inclination (modify hsra.mod)
  1. One node in B,  $v_{\text{LOS}}$ , inclination.
  2. Two nodes in B,  $v_{\text{LOS}}$ , inclination.

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

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
```

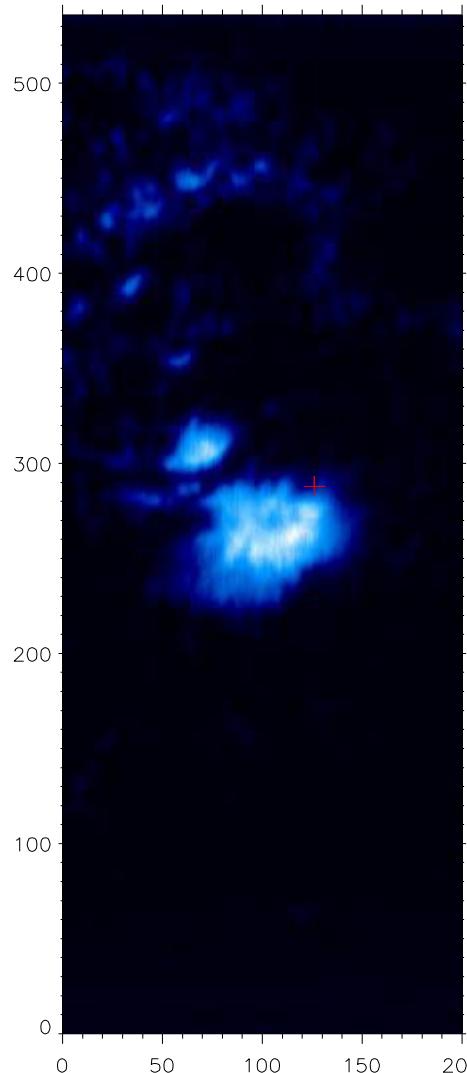
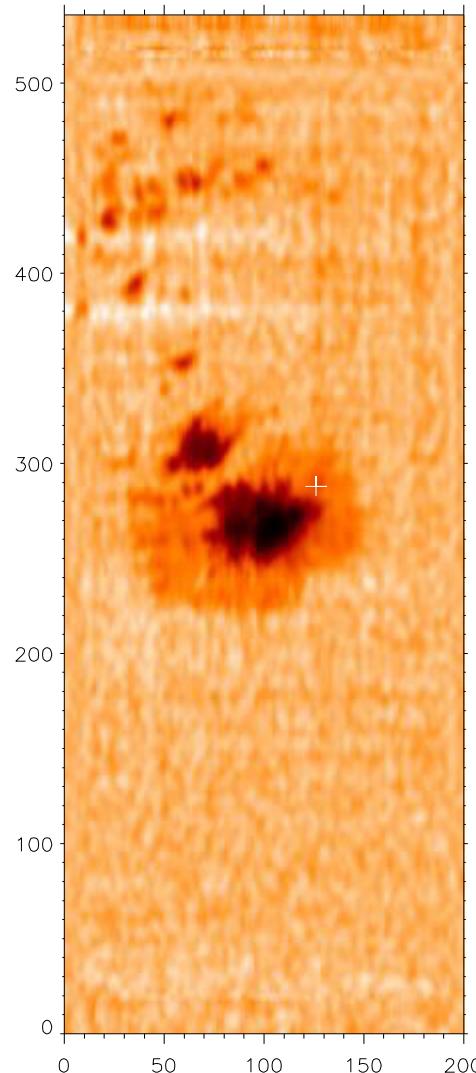
And the region of sensitivity by:

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

# Exercise 4

## Inversion of SPINOR data

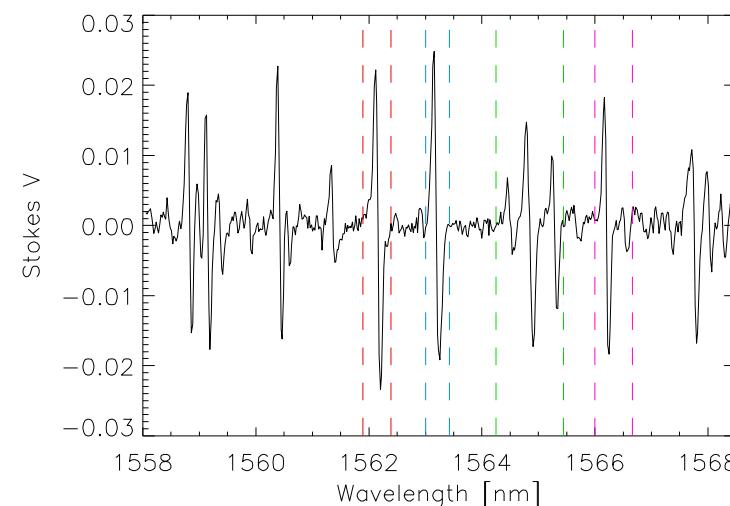
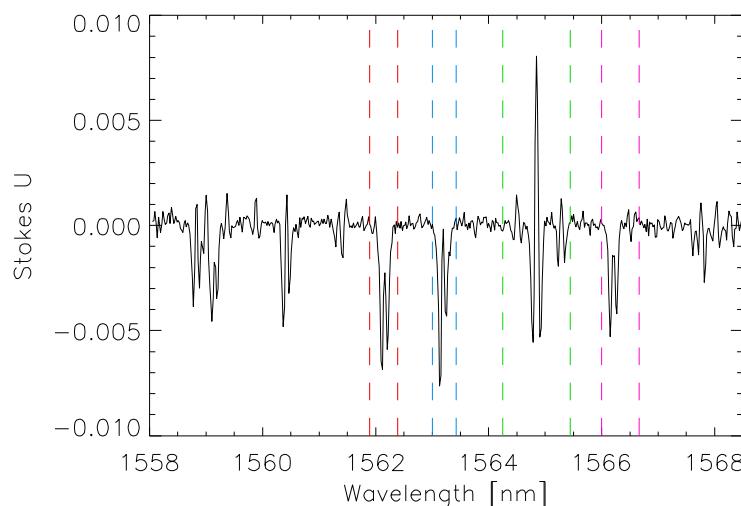
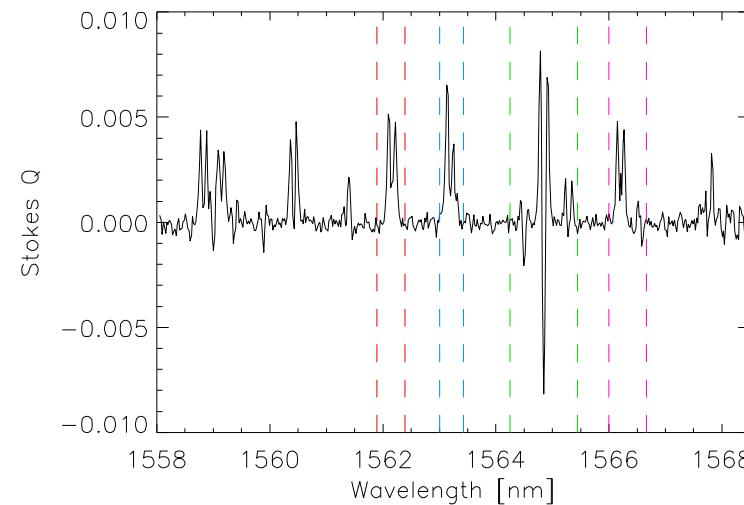
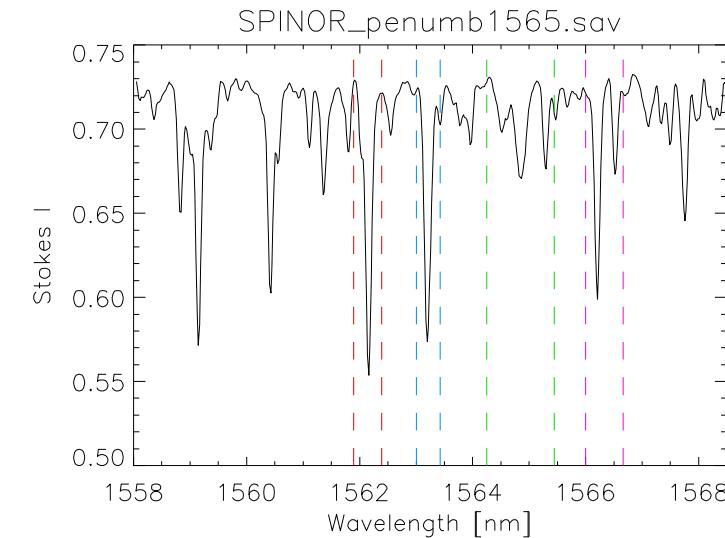
SPINOR: Spectro Polarimeter for Infrared and Optical Regions (NSO/HAO)  
@ Dunn Solar Telescope on Sacramento Peak



# 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 $\sim 10^5$ , 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....

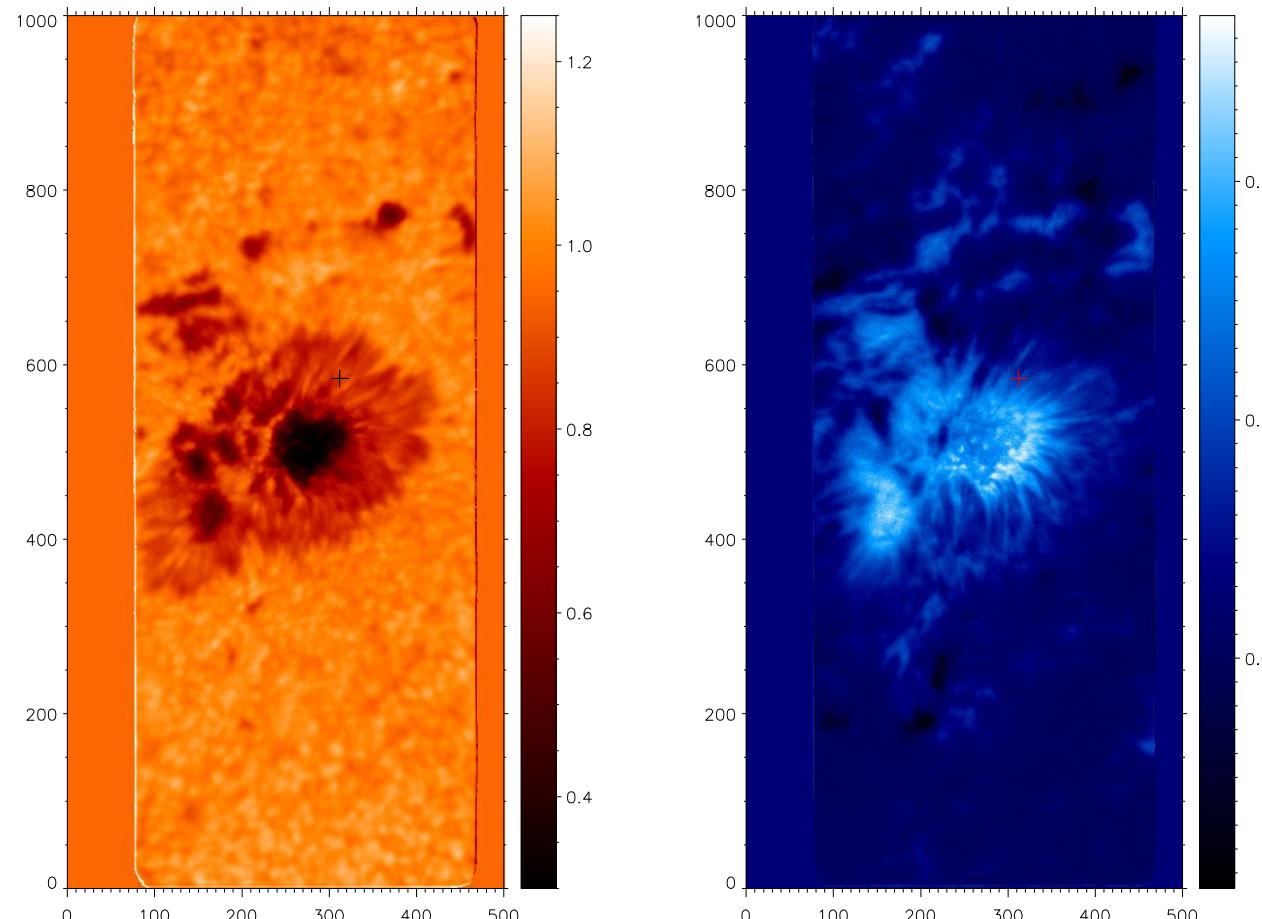
# Exercise 7

## Inversion of IBIS profiles

IBIS: Interferometric Bidimensional Spectropolarimeter (INAF\_Arcetri OBS/NSO)

@ Dunn Solar Telescope on Sacramento Peak

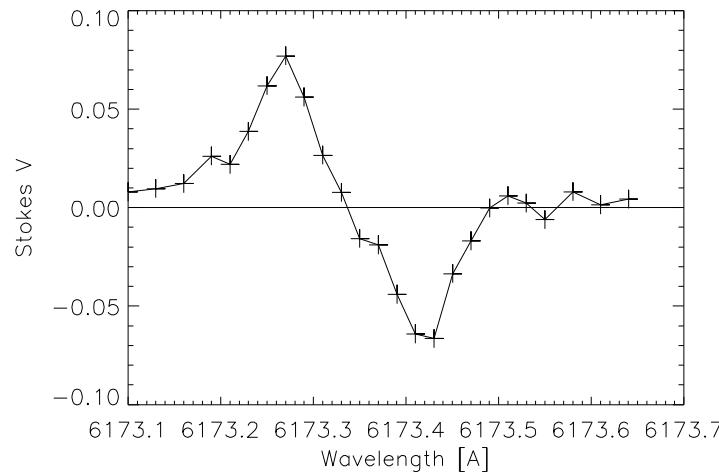
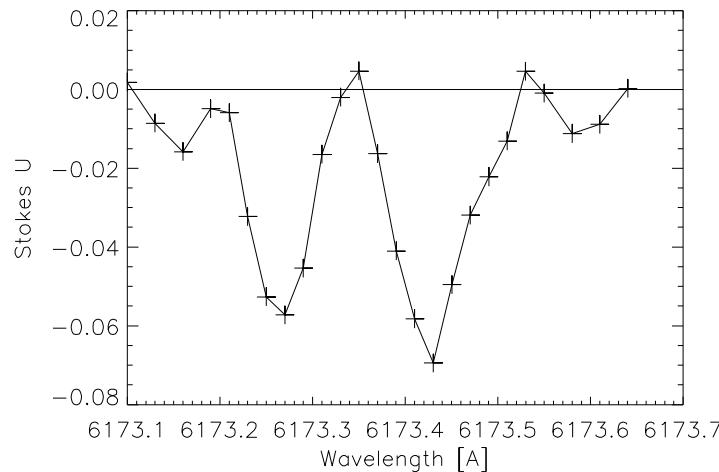
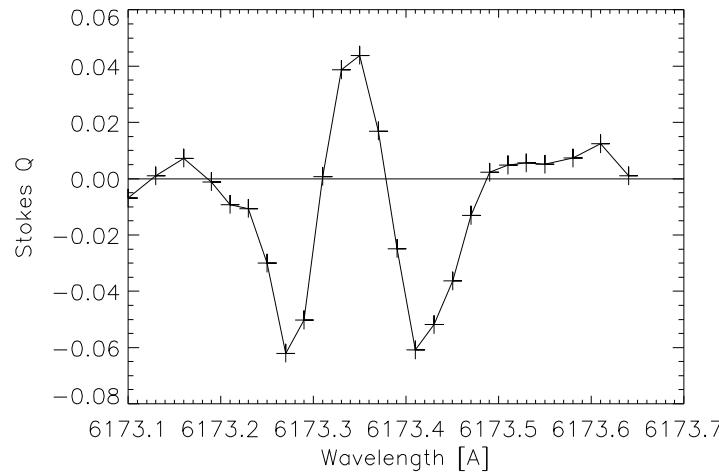
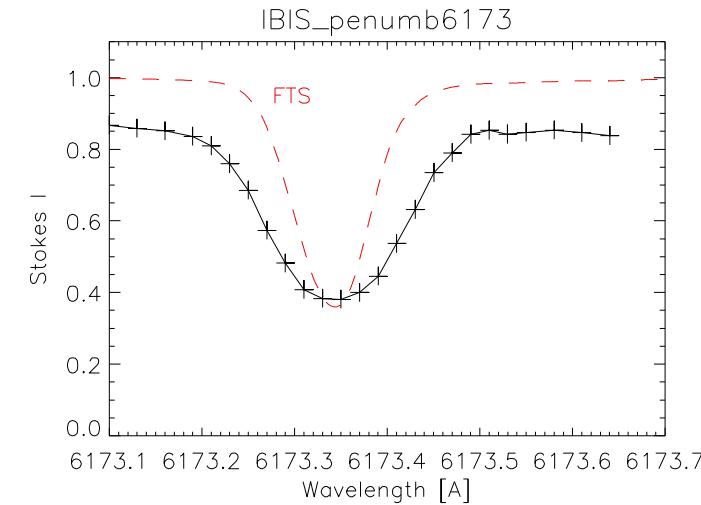
Penumbra observed at Fe I 6173 Å



# 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 $\sim$ 500, sequential spectral sampling of Fe I 617.3 nm  
(30 wavelengths in  $\sim$ 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)

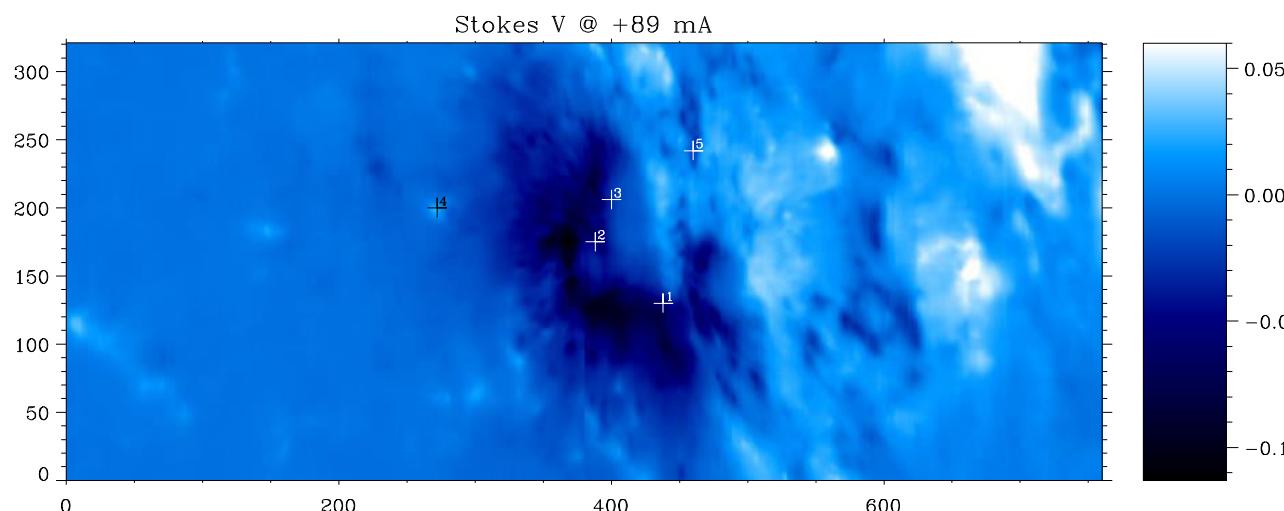
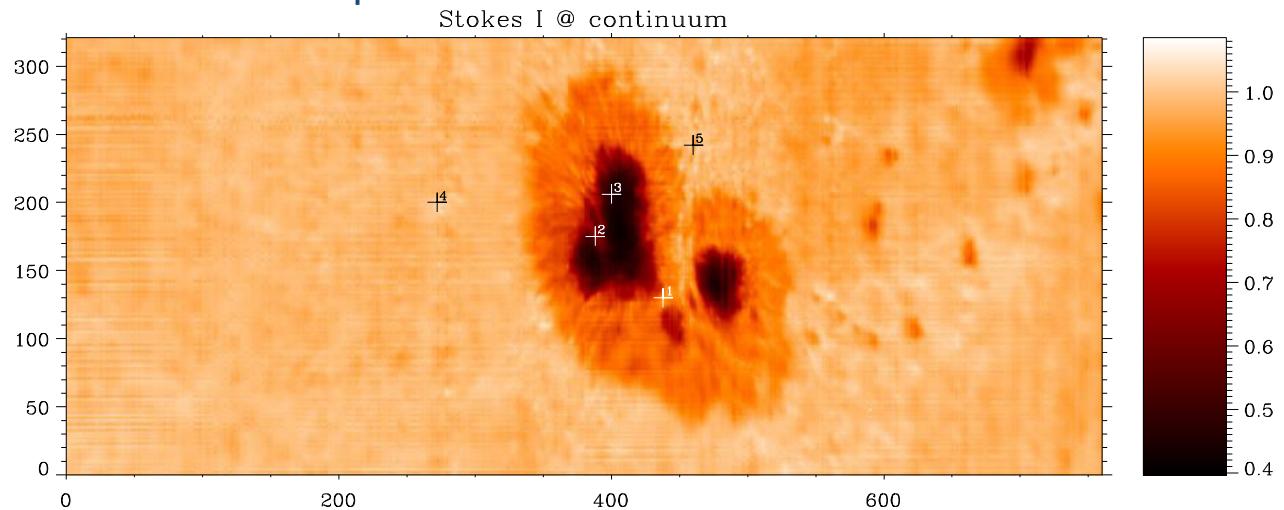
Example of Stokes profiles observed with a **Fabry-Pérot interferometer**.  
Extremely high spatial resolution, but modest spectral resolution ( $\sim$ 50 mA at 617 nm).  
Sequential sampling of line means first and last wavelengths are observed  $\sim$ 30 s apart.

# Exercise 8

## Inversion of FIRS profiles

FIRS: Facility Infrared Spectropolarimeter (Univ. Hawai'i/NSO)

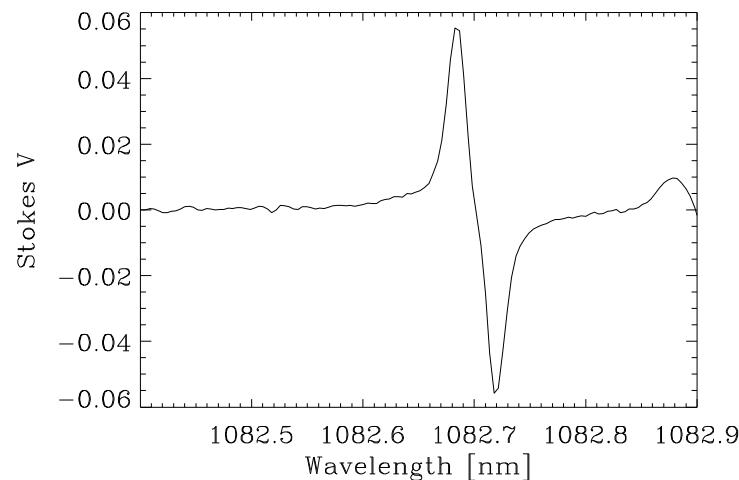
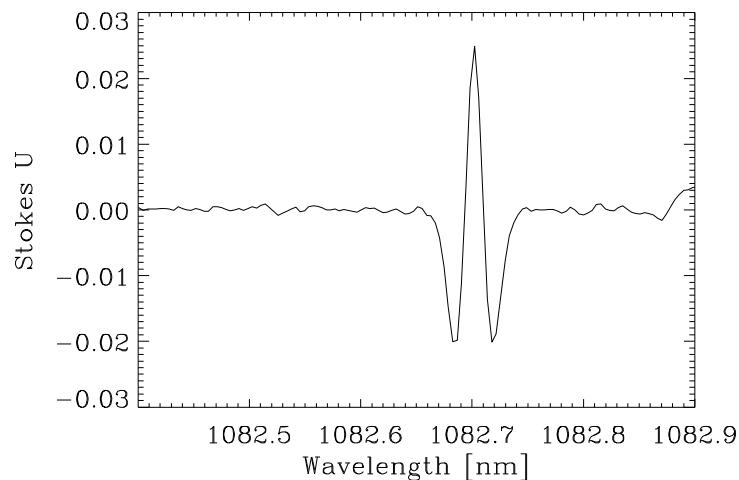
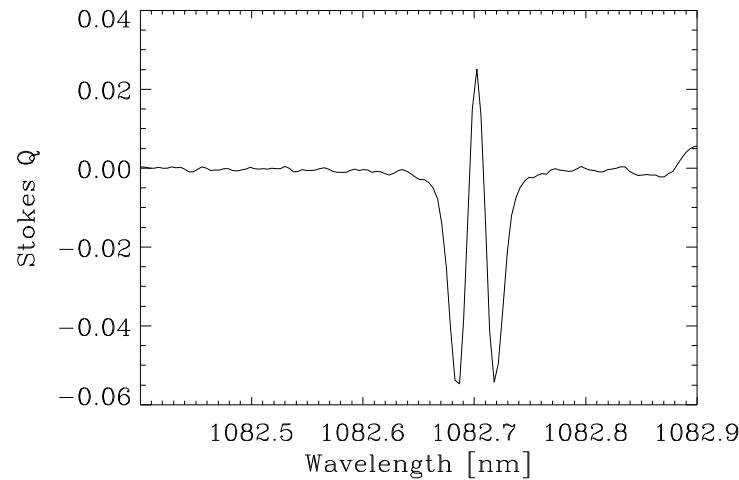
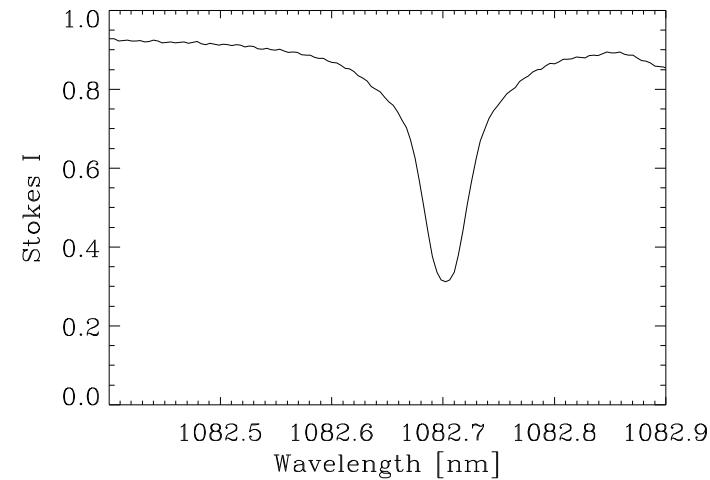
@ Dunn Solar Telescope on Sacramento Peak



# 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)  
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1. Restore “FIRS\_profiles.sav”, write the profiles of the Si line in SIR format and invert Stokes I & V  
Including macro and micro, for several points over the active region. I suggest five points  
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 containing 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  $v_{\text{LOS}}$  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 program 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).