The art of Stokes inversions

Luis R. Bellot Rubio
Instituto de Astrofísica de Andalucía (CSIC), Spain
National Astronomical Observatory, Japan

Outline

- What is an inversion technique?
- How do they work?
- ME inversions
- Accounting for asymmetric Stokes profiles
- Be careful with the choice of model atmosphere!
- Available codes
- Tips and tricks
- Stray-light considerations
- Running SIR
  - Input files
  - Visualization of results

What is an inversion technique?

- Any method used to infer the physical conditions of the atmosphere from the interpretation of Stokes profiles
  - Center-of-gravity method, bisector analyses, …
  - Forward modeling
  - PCA, artificial neural networks
  - Least-squares fitting

- What to expect: a model atmosphere capable of reproducing the observations…. nothing else!

Radiative transfer

- The Stokes parameters obey the RTE

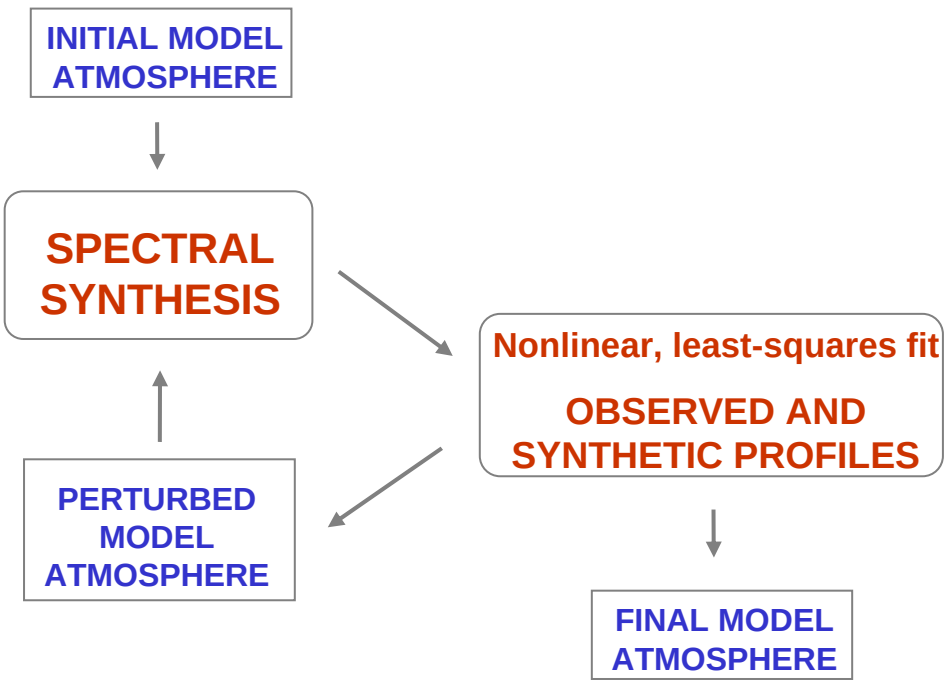
$$\frac{d}{d\tau}\begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix} = \begin{pmatrix} \eta_I & \eta_Q & \eta_U & \eta_V \\ \eta_Q & \eta_I & \rho_V & -\rho_U \\ \eta_U & -\rho_V & \eta_I & \rho_Q \\ \eta_V & \rho_U & -\rho_Q & \eta_I \end{pmatrix} \begin{pmatrix} I-S \\ Q \\ U \\ V \end{pmatrix}$$

(Unno 1956; Rachkovsky 1962)

- $\eta_{I,Q,U,V}$ and $\rho_{Q,U,V}$ depend on $\mathbf{a} \equiv (B, \gamma, \chi, v_{LOS}, T, P_e, v_{mic})$
- This means that
  - Four Stokes parameters needed to understand just one of them
  - Proper interpretations of the Stokes vector require a good knowledge of the atmosphere (**a**)

Least-square inversions

- The complete line transfer problem has to be solved
- Self-consistent inferences → Inversion techniques



Advantages:

- No simplifying assumptions
- Full Stokes vector fitted
- Complex model atmospheres
- All atmospheric parameters inferred at the same time

How do they work?

- Inversion driven by χ^2-minimization:

$$\chi^2(\mathbf{a}) = \sum \left[I_{obs}(\lambda_i) - I_{syn}(\lambda_i, \mathbf{a}) \right]^2$$

- Linearization: Levenberg-Marquardt algorithm

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

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

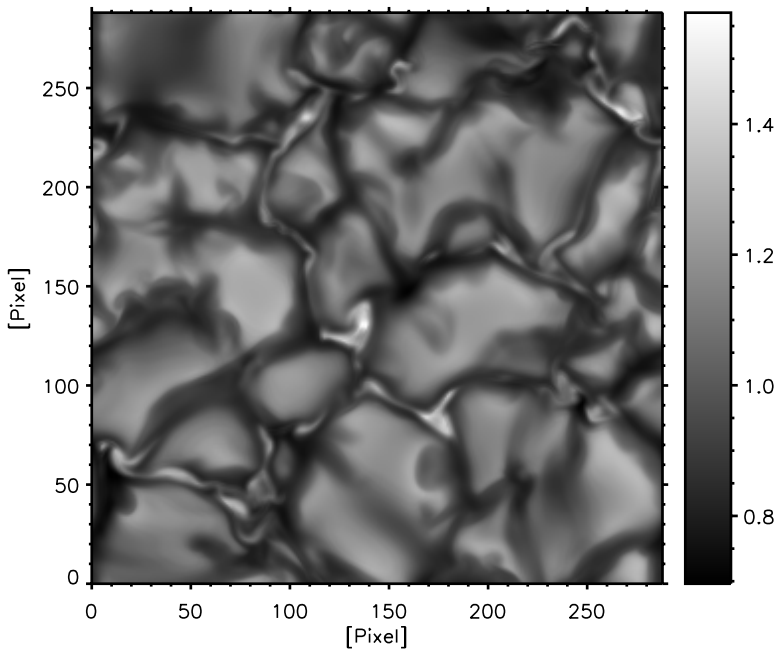
- Regularization techniques (*when in doubt, smooth*)
  - Penalty function, or
  - Modified SVD method (Ruiz Cobo & del Toro Iniesta 1992)

Inversions based on ME atmospheres

- ME atmosphere:
  - Source function is linear with optical depth
  - Absorption matrix does not vary with optical depth
- Analytical Stokes profiles
- Fast inversion
- Smooth maps of physical quantities
- Results are relatively accurate and easy to interpret

ME inversions of high spatial resolution profiles

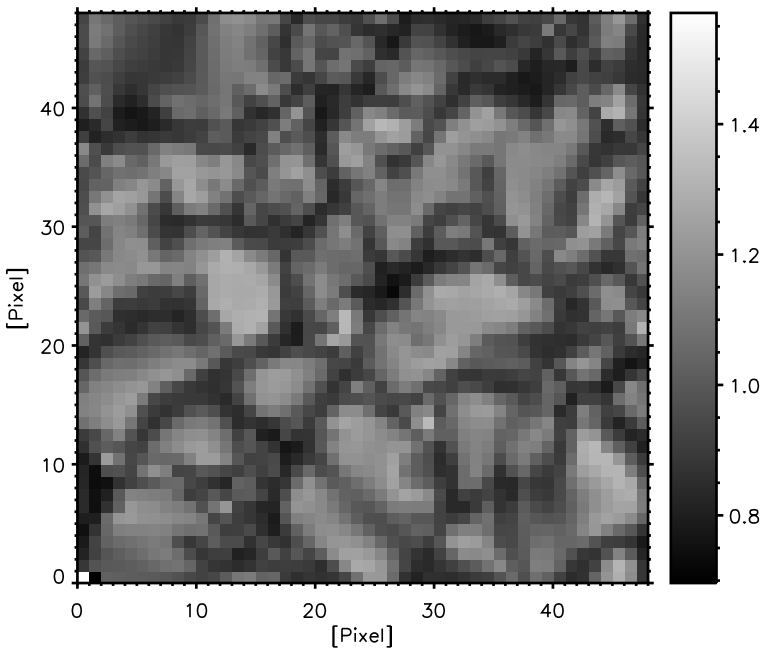
MHD simulations (Vögler et al. 2005)

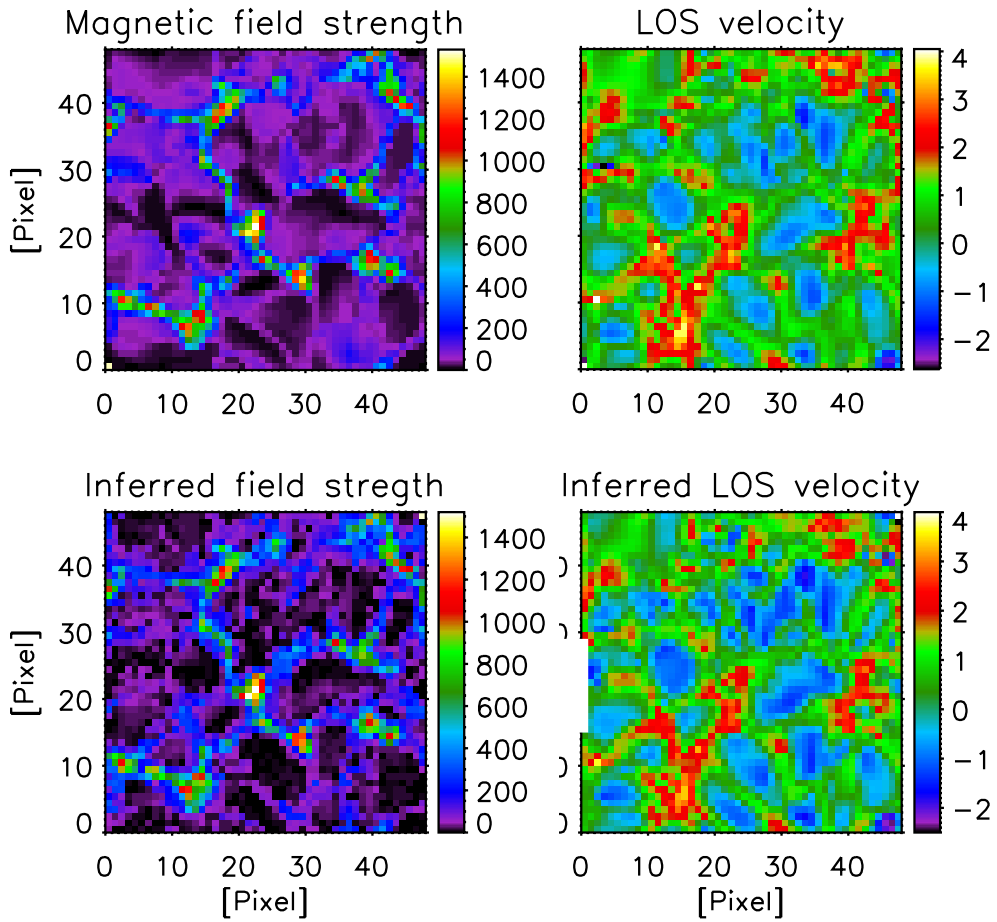


- Fe I 630.1 and 630.2 nm profiles degraded to HINODE/SP pixel size

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 pixel size
- Maps of inferred B and v_{Los} very similar to real ones!

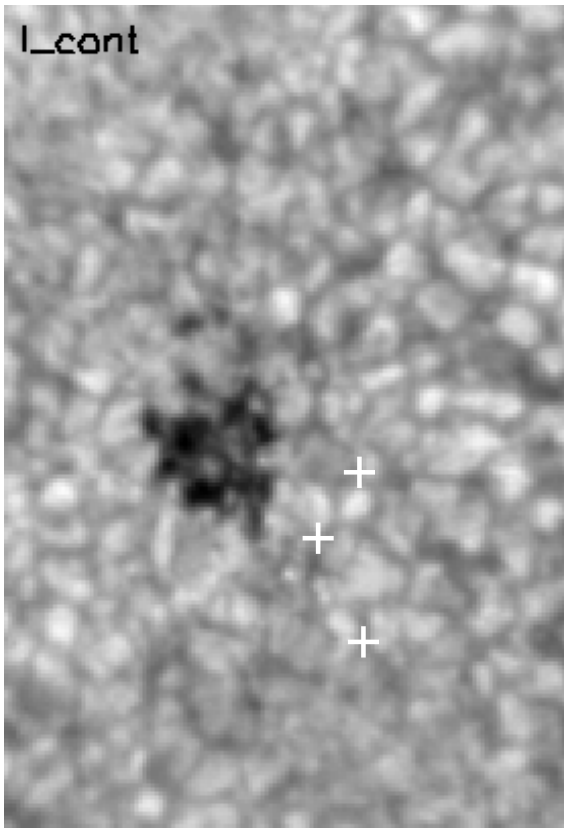
Orozco Suárez et al. 2007, ApJL

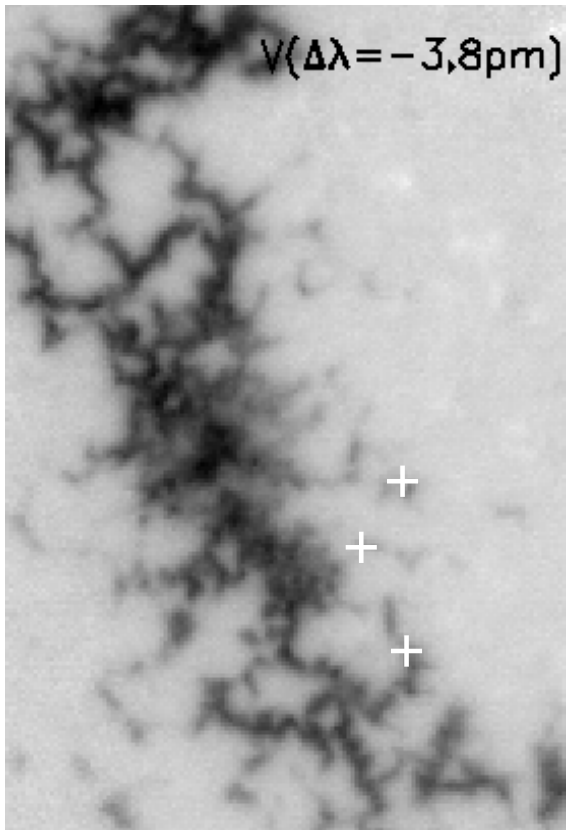
Inversions based on ME atmospheres

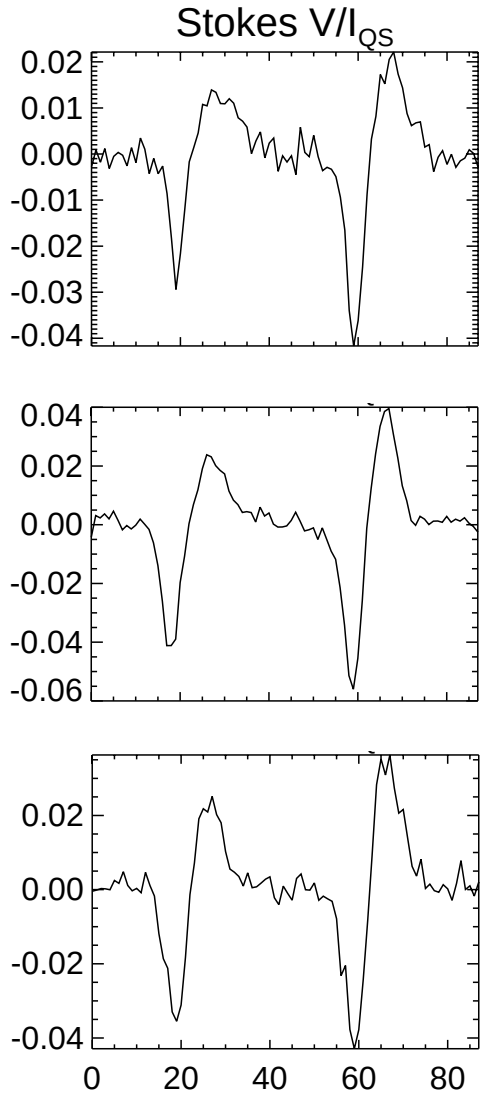
- ME atmosphere:
  - Source function is linear with optical depth
  - Absorption matrix does not vary with optical depth
- Analytical Stokes profiles
- Fast inversion
- Smooth maps of physical quantities
- Results are easy to interpret

- Simplistic treatment of radiation transfer
- Little thermal information. No height variations
- Cannot account for asymmetric Stokes profiles

Asymmetric Stokes profiles





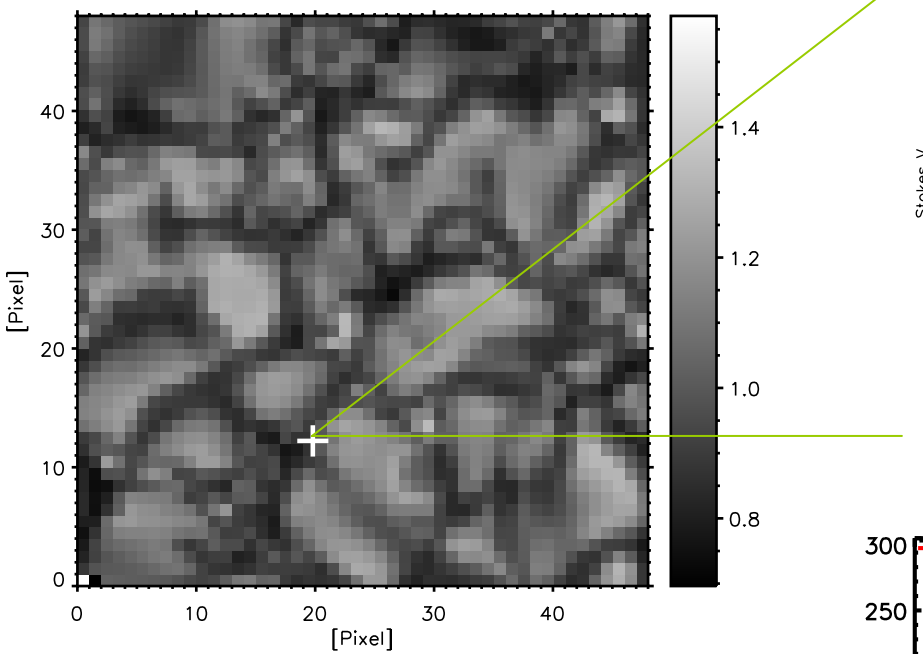


- KIS/IAA Visible Imaging Polarimeter + TESOS + KAOS
- VTT, Observatorio del Teide
- Spatial resolution: ~0.4"
- Pore near disk center, Fe I 630.15 and 630.25 nm

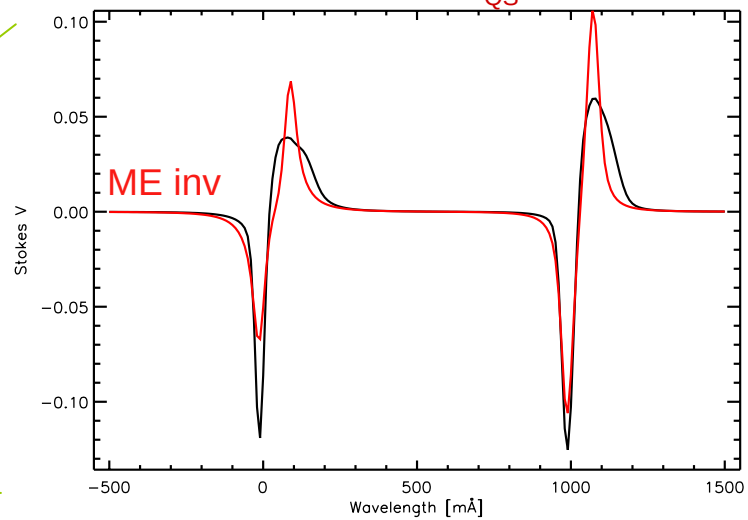
Bellot Rubio et al. (2007)

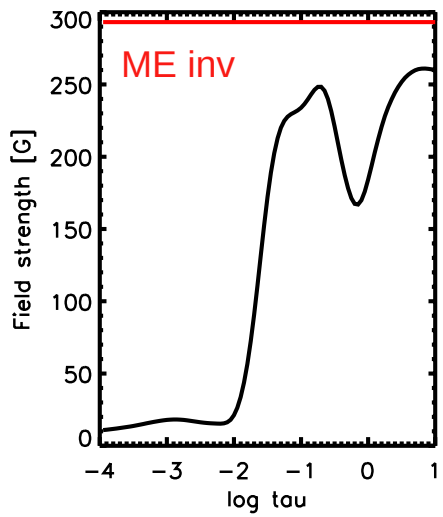
ME inversions of asymmetric profiles

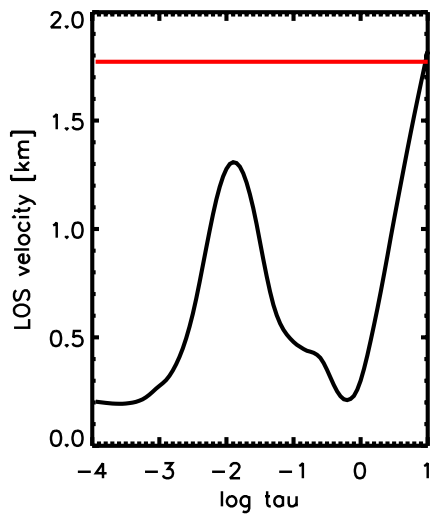
MHD simulations (Vögler et al. 2005)



Stokes V/I_{QS}







- Stokes profiles not well fitted
- ME results are some kind of "average" of physical parameters along the LOS

The origin of asymmetries

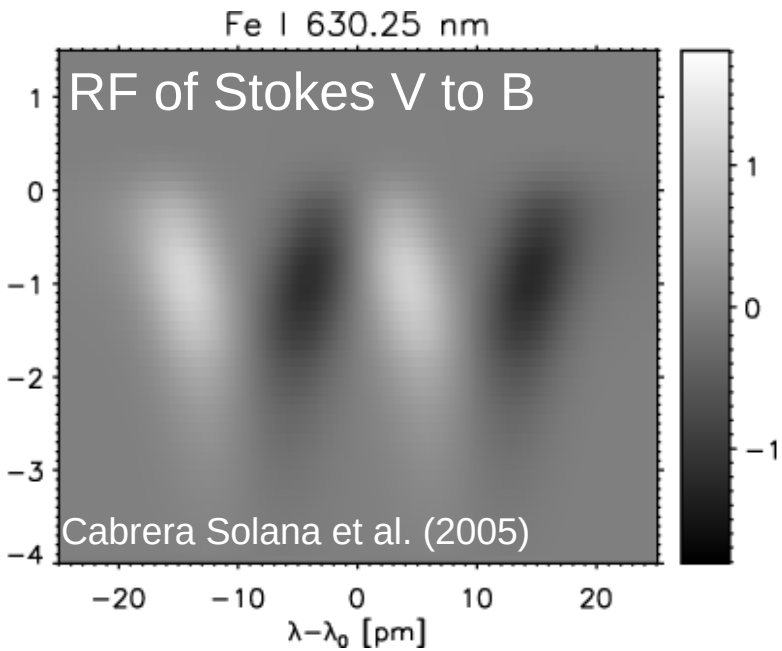
Amplitude asymmetry/
Multi-lobed Stokes profiles

Different magnetic atmospheres coexisting in resolution element

Area asymmetry

Gradients/discontinuities of physical parameters along LOS

Auer & Heasley (1978)

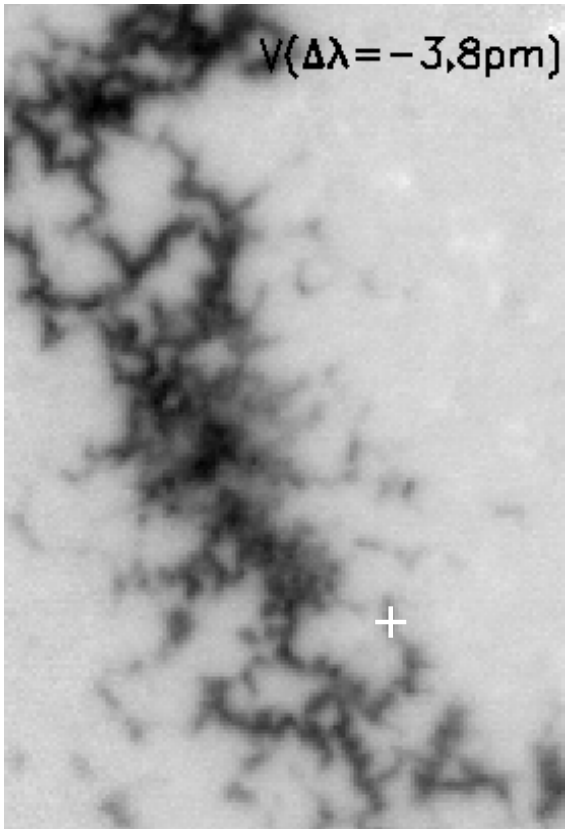


The area asymmetry gives information on the height variation of atmospheric parameters

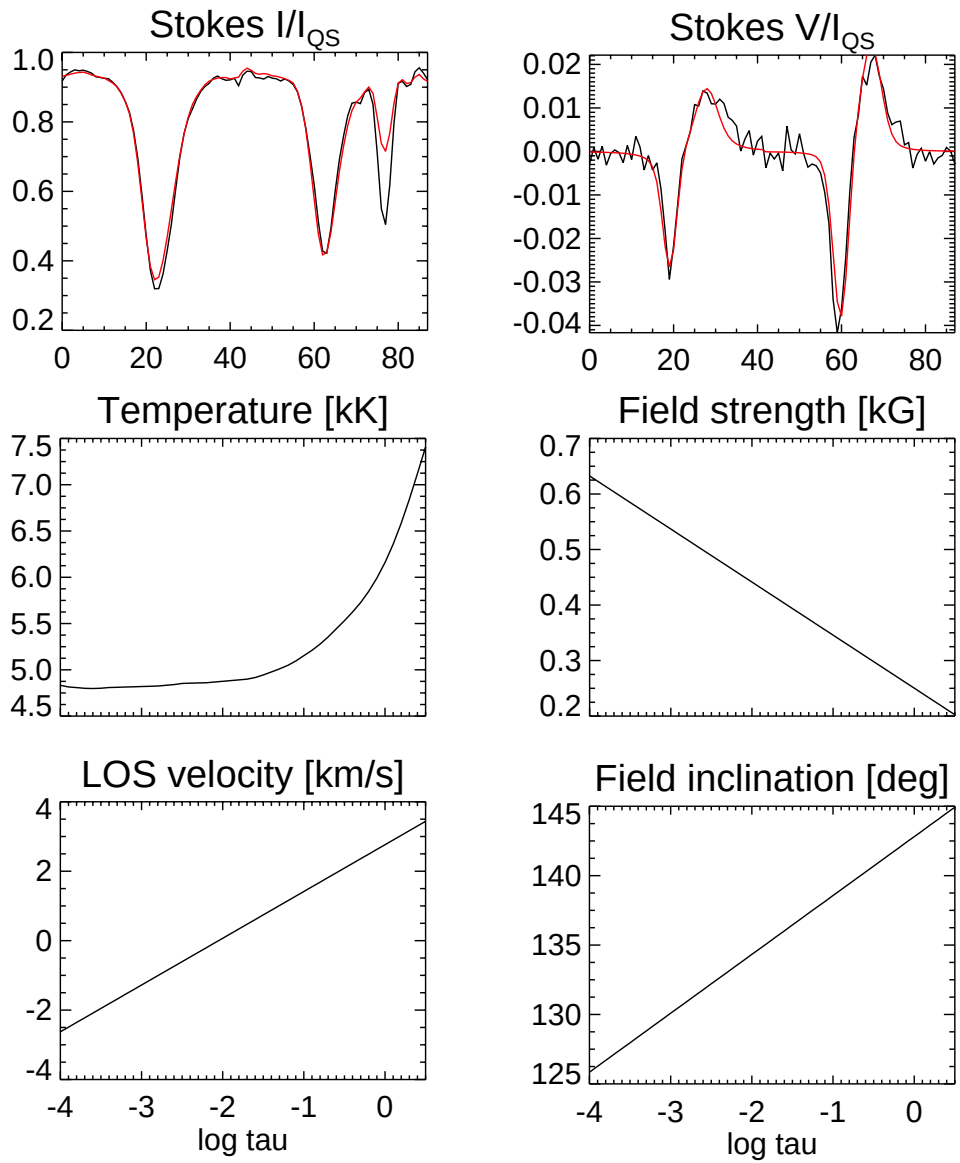
Accounting for asymmetries

- 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

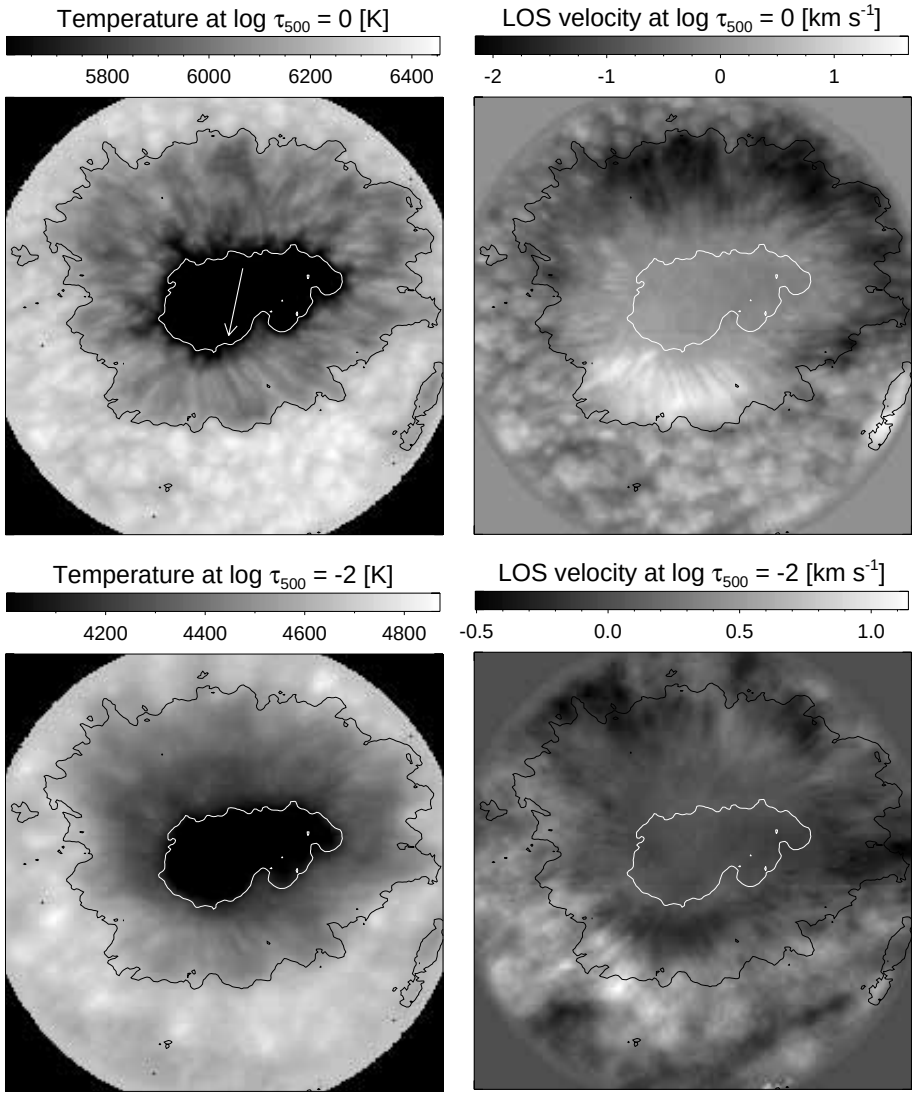
Accounting for asymmetries

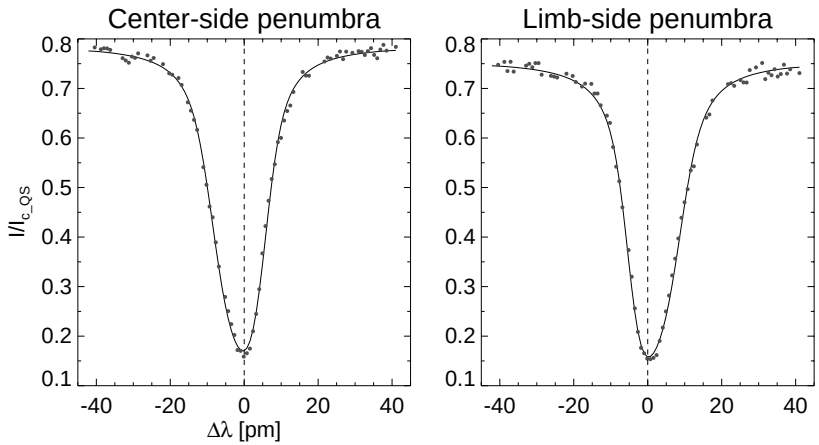


- VIP + TESOS + KAOS
- SIR with 10 free parameters
- Bellot Rubio et al. (2007)



Inversions with gradients





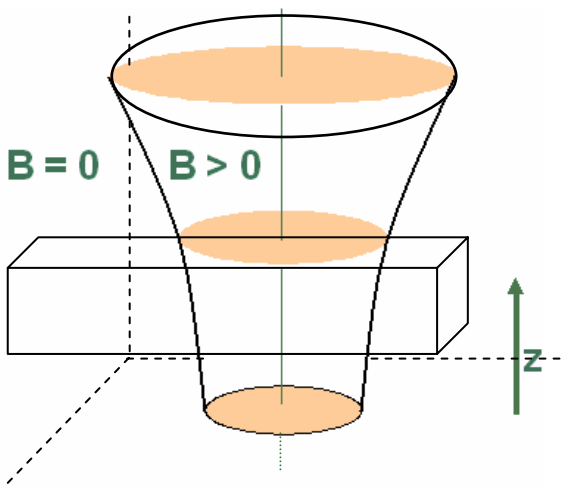
- Spatial resolution ~ 0.5"
- Intensity profiles of Fe I 557.6 nm
- SIR with 7 free parameters
- Thermal/kinematic structure of AR 0019 at different heights in the photosphere

Bellot Rubio, Schlichenmaier, & Tritschler 2006, A&A 453, 1117

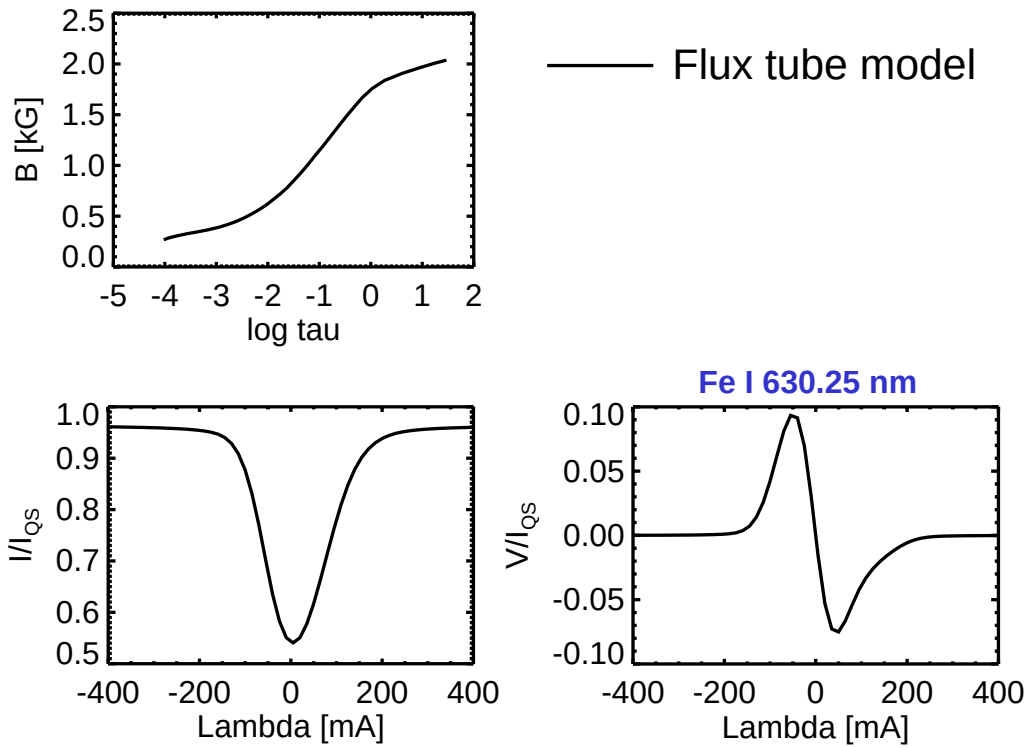
Be careful with the atmospheric model!

Inversion results change if the physical model is changed

Models are often simplistic and do not describe the real atmosphere



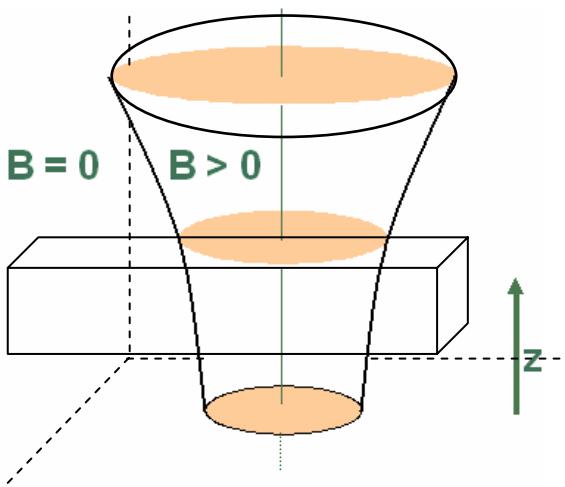
Magnetic flux tubes in facular regions



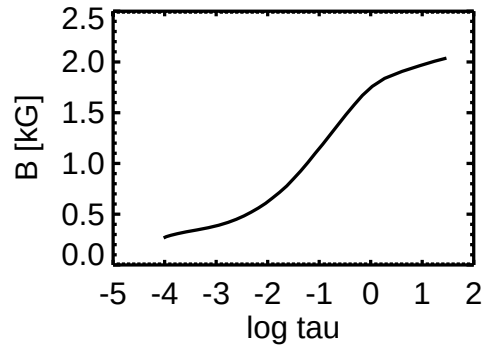
Be careful with the atmospheric model!

Inversion results change if the physical model is changed

Models are often simplistic and do not describe the real atmosphere



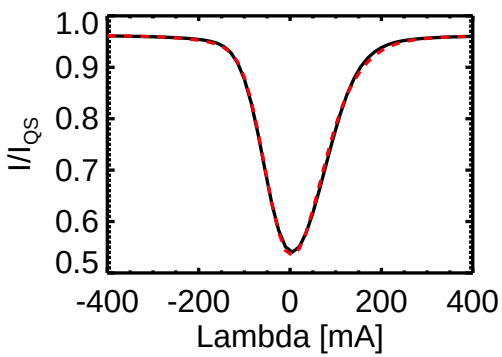
Magnetic flux tubes in facular regions

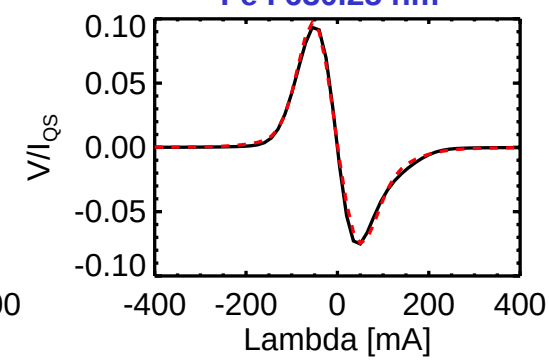


Flux tube model

Best-fit 1C model

Fe I 630.25 nm

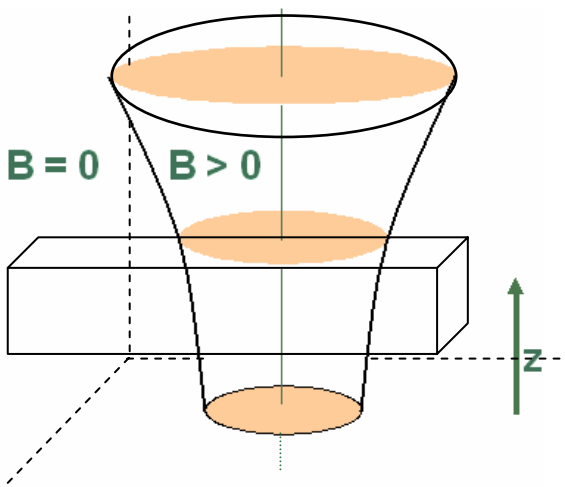




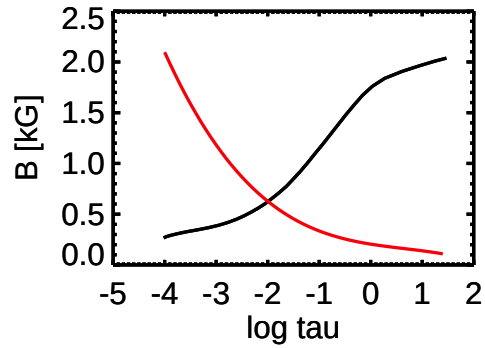
Be careful with the atmospheric model!

Inversion results change if the physical model is changed

Models are often simplistic and do not describe the real atmosphere



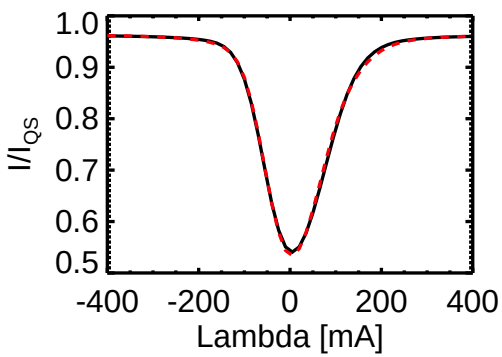
Magnetic flux tubes in facular regions

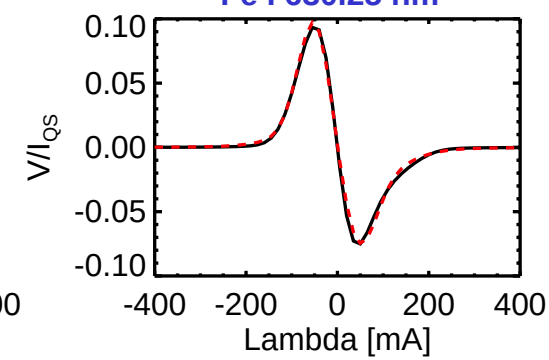


Flux tube model

Best-fit 1C model

Fe I 630.25 nm





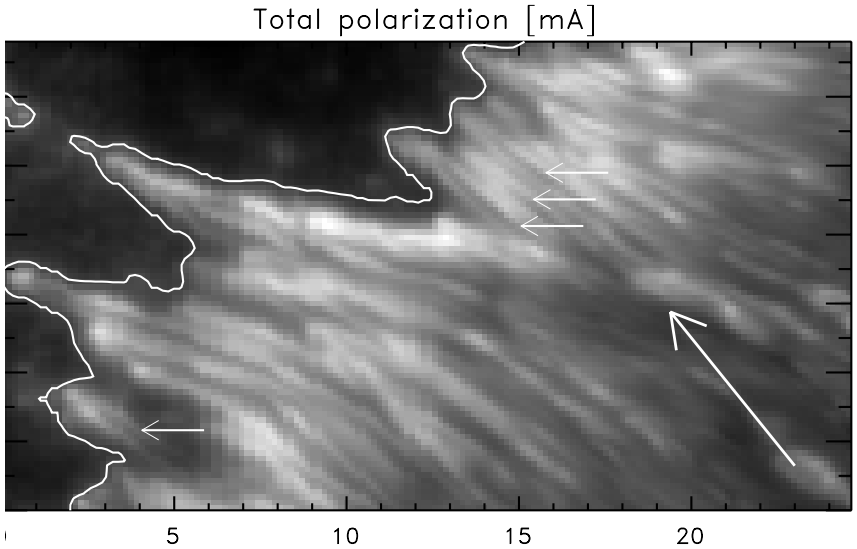
Available codes for inversions with gradients

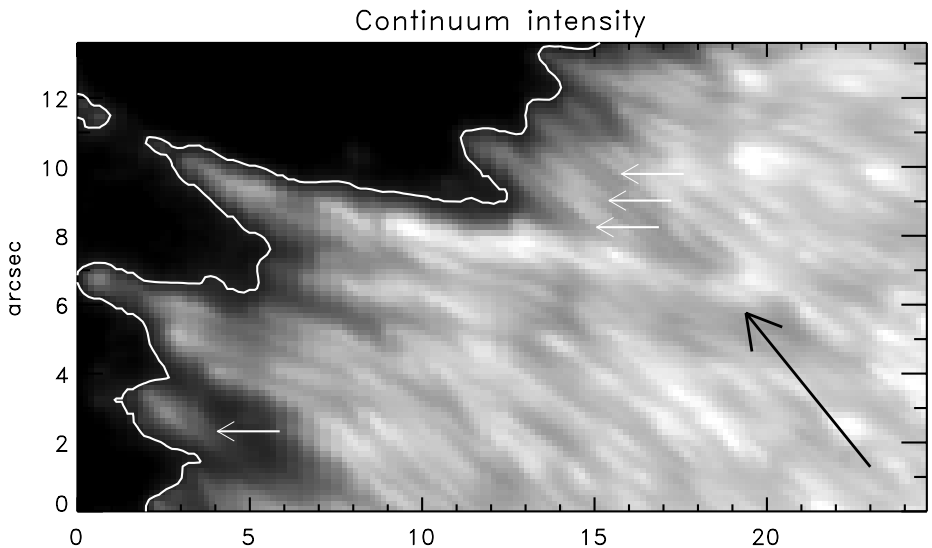
SIR	Ruiz Cobo & del Toro Iniesta (1992)	1C & 2C atmospheres, arbitrary stratifications, any photospheric line
SIR/FT	Bellot Rubio et al. (1996)	Flux tube model, arbitrary stratifications, any photospheric line
SIR/NLTE	Socas-Navarro et al. (1998)	NLTE line transfer, arbitrary stratifications
SIR/GAUS	Bellot Rubio (2003)	Uncombed penumbral model, arbitrary stratifications
SIR/JUMP	Bellot Rubio (2007)	Canopy-like atmospheres
SPINOR	Frutiger & Solanki (2001)	1C & 2C atmospheres, arbitrary stratifications, any photospheric line, molecular lines, flux tube model, uncombed model
LILIA	Socas-Navarro (2001)	1C atmospheres, arbitrary stratifications
MISMA IC	Sánchez Almeida (1997)	MISMA model, arbitrary stratifications, any photospheric line

Tips and tricks

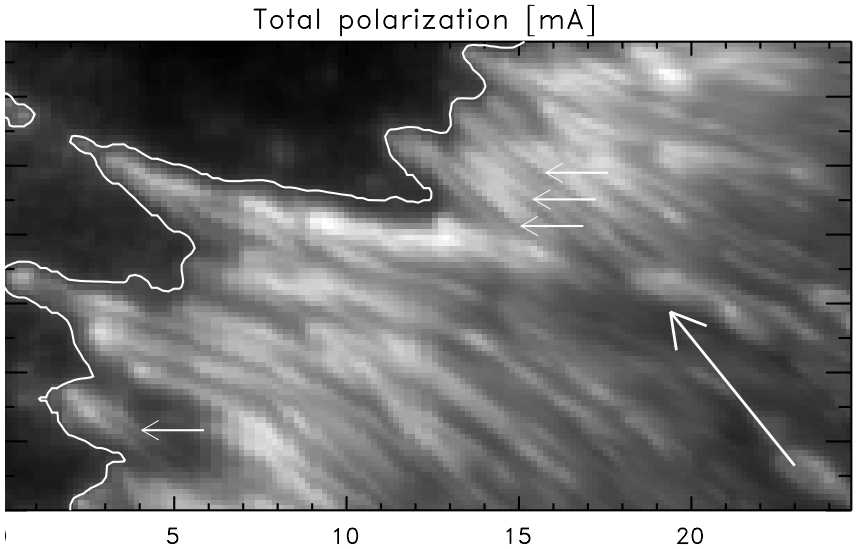
- First of all, look at the profiles
- Try a ME inversion, it usually works
  - If the V profiles are very asymmetric, fit only I, Q, and U
- Examine the fits: are they reasonably good?

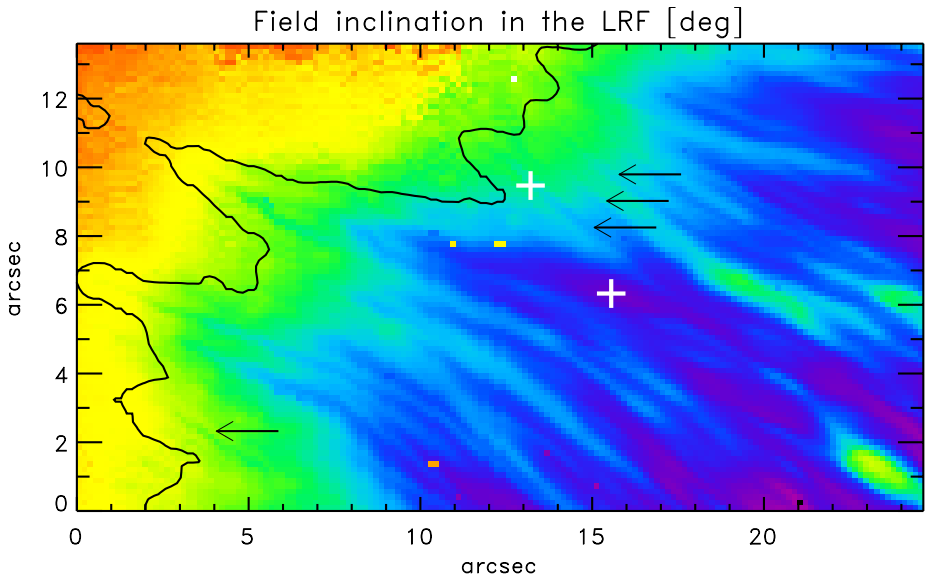
1C SIR inversion of Hinode/SP data

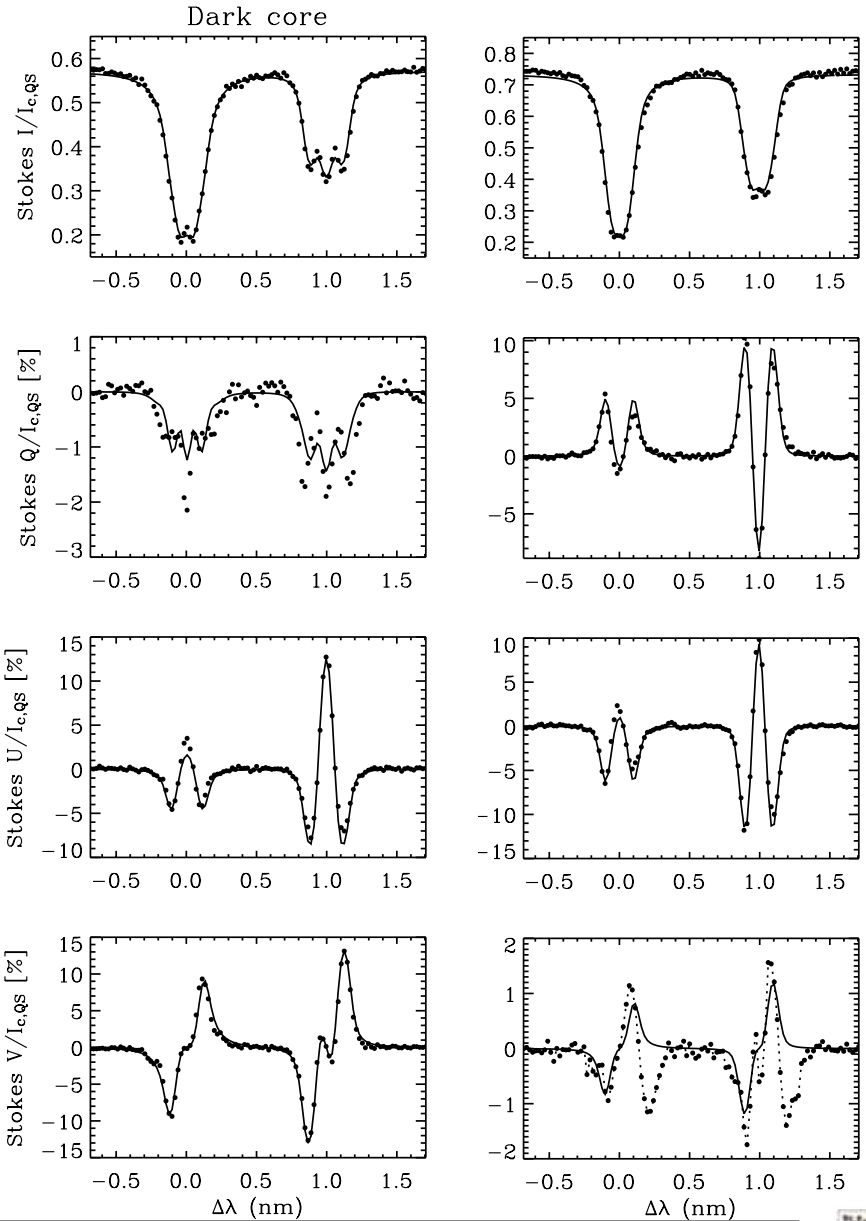




1C SIR inversion of Hinode/SP data







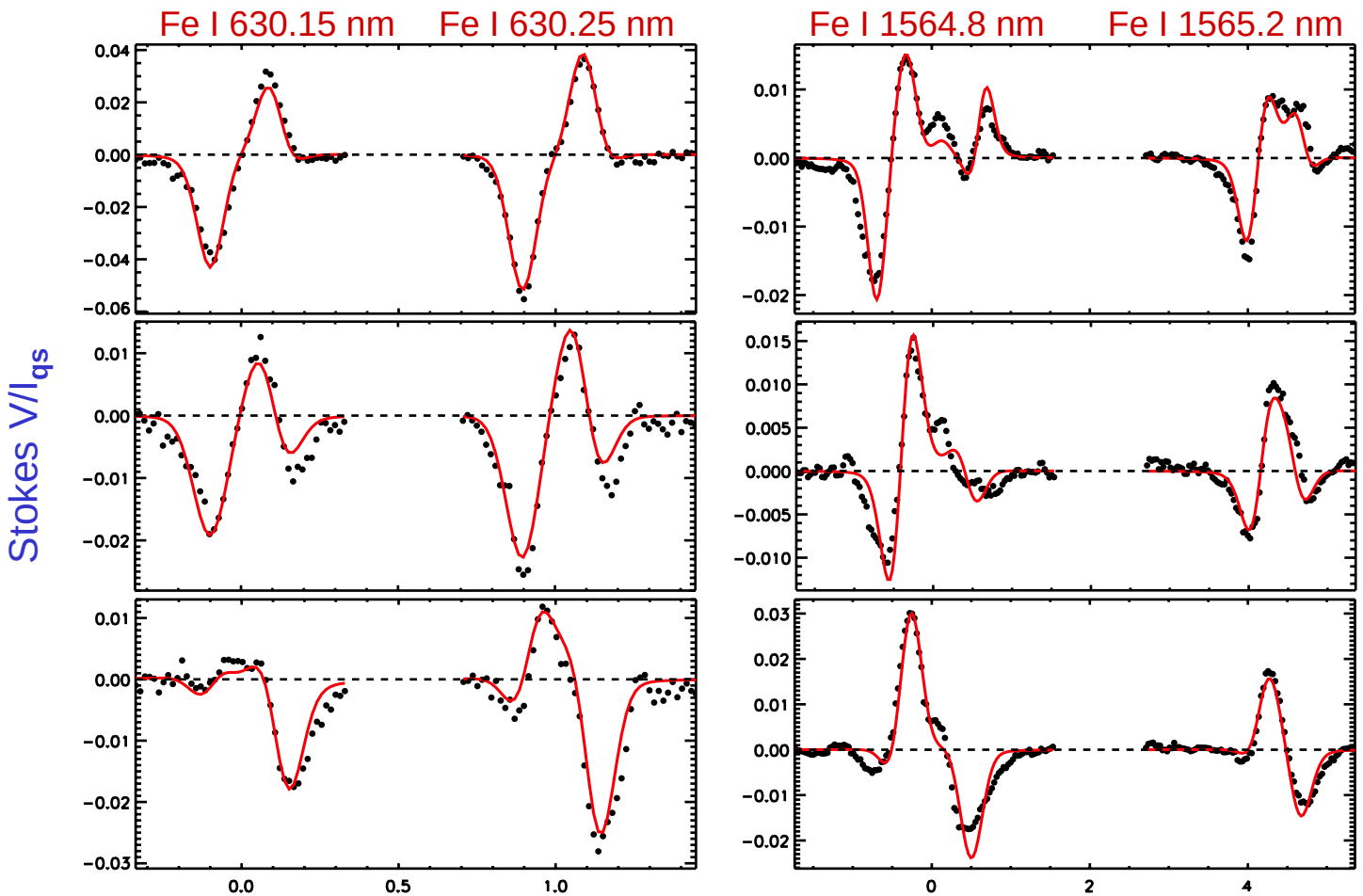
Tips and tricks

- First of all, look at the profiles
- Try a ME inversion, it usually works
  - If the V profiles are very asymmetric, fit only I, Q, and U
- Examine the fits: are they reasonably good?
- Identify
  - Pixels with bad fits and/or large asymmetries
  - Regions where interesting physical processes occur
- Run SIR inversions on these pixels
  - Which model are you going to use?

    1C model, 2C model, flux tube model, uncombed model?

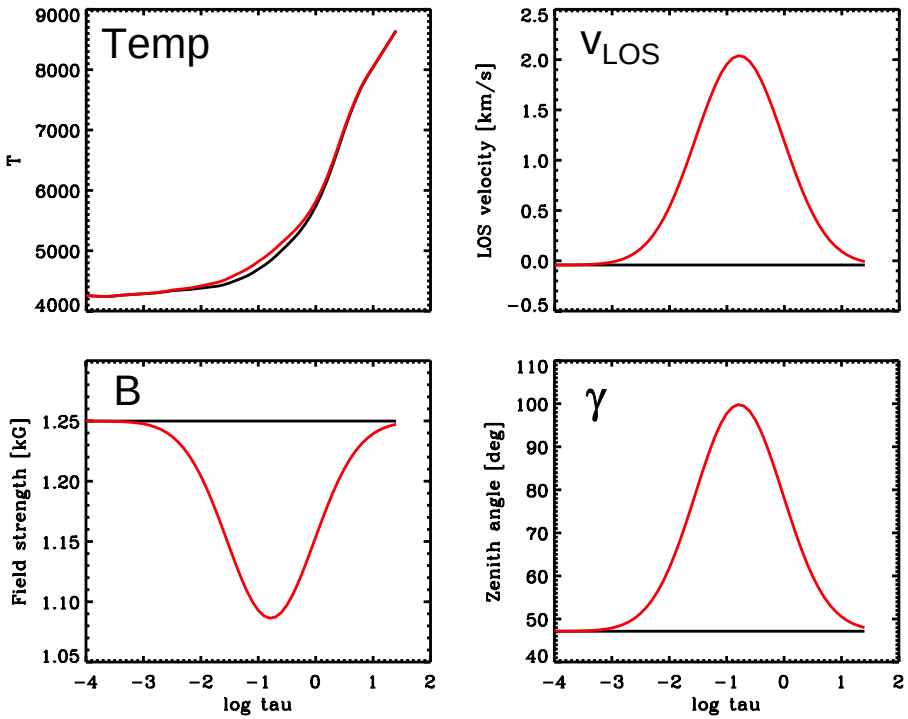
Uncombed inversion of penumbral profiles

SIR/GAUS inversion of simultaneous visible and IR observations



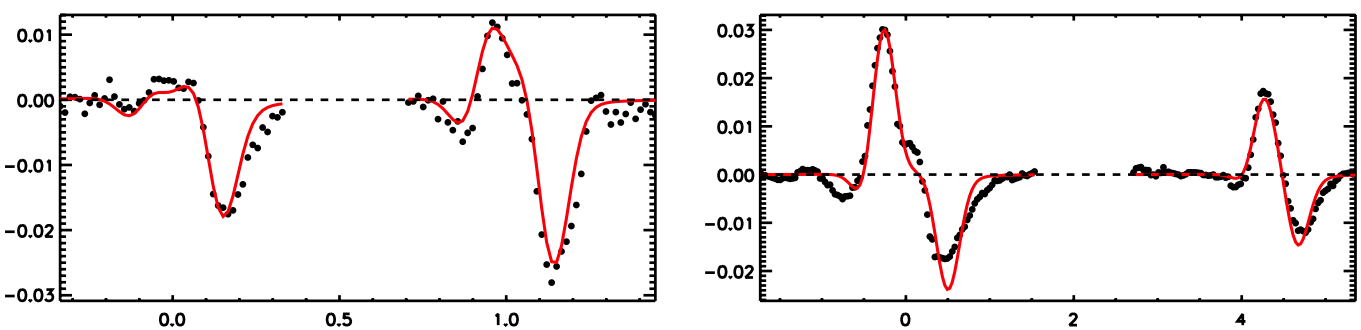
Beck et al. (in prep)

Uncombed inversion of penumbral profiles



Best-fit uncombed model

Visible and IR profiles observed at 1" are compatible with flux tubes embedded in a more vertical and stronger background field



Beck et al. (in prep)

Tips and tricks

- First of all, look at the profiles
- Try a ME inversion, it usually works
  - If the V profiles are very asymmetric, fit only I, Q, and U
- Examine the fits: are they reasonably good?
- Identify
  - Pixels with bad fits and/or large asymmetries
  - Regions where interesting physical processes occur
- Run SIR inversions on these pixels
  - Which model are you going to use?
    1C model, 2C model, flux tube model, uncombed model?
  - Use ME results as initialization
  - Give more weight to the strangest Stokes parameter
  - Keep it simple! See if linear stratifications (2 nodes) are sufficient
- Ask yourself if the retrieved model atmosphere makes sense!!
- You have experts in-house: ask them for advice (Jan-san)

Running SIR: input files

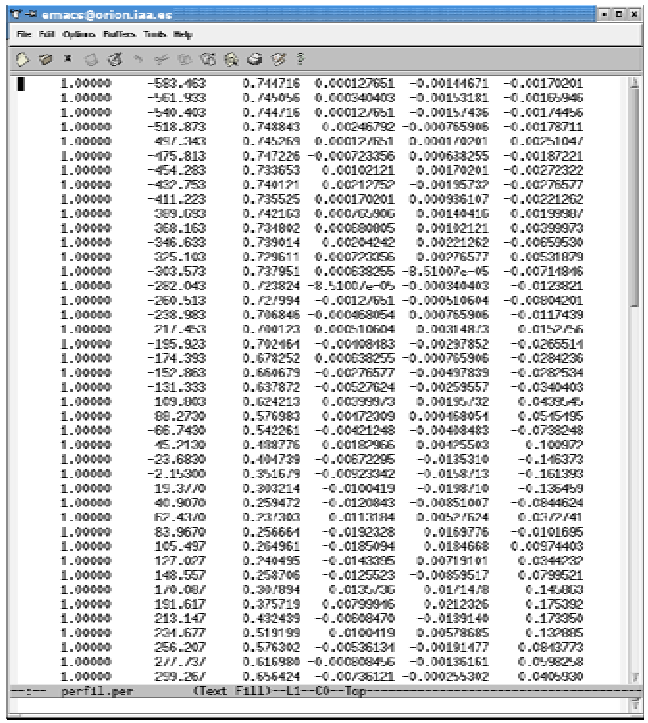
emacs@orion.iaa.es

File Edit Options Buffers Tools Help

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

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

PROFILE FILE



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

lperfiles.pro

wperfiles.pro

Running SIR: input files

emacs@orion.iaa.es

File Edit Options Buffers Tools Help

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

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

WAVELENGTH GRID FILE

emacs@dhcp-200-191.mtk.nao.ac.jp

File Edit Options Buffers Tools Help

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

Line and blends indices   :   Initial lambda     Step      Final lambda
(in this order)                     (mA)          (mA)          (mA)

1.2                       :      -645.9.         21.53.      1743.93
```

: malla.grid (Text Fill) L/ C1/ All

Running SIR: input files

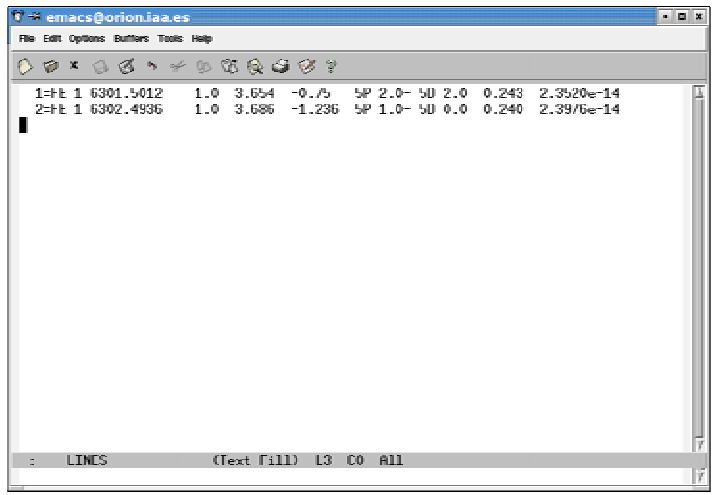
emacs@orion.iaa.es

File Edit Options Buffers Tools Help

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

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

ATOMIC PARAMETER FILE



Line index | Atom | λ | E | χ | log gf | transition

Running SIR: input files

emacs@orion.iaa.es

File Edit Options Buffers Tools Help

```
Number of cycles              (*):1            ! (0=synthesis)
Observed profiles             (*):perfil.per   !
Stray light file                 :             ! (none=no stray light contam)
PSF file                         :             ! (none=no convolution with PSF)
Wavelength grid file          (s):malla.grid   ! (none=automatic selection)
Atomic parameters file           :LINES        ! (none=DEFAULT LINES file)
Abundances file                  :THEVENIN     ! (none=DEFAULT ABUNDANCES file)
                                               !
Initial guess model 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
--:**  sir.trol          (Text Fill)--
```

MODEL FILE

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  7.4904E-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
```

leemod.pro

escribemod.pro

modelador2.x

equilibrium.x

geometrical.x

$\log \tau$ T P_e v_{mic} B v_{LOS} γ φ z [km] P_g ρ

Running SIR/GAUSS: input files

muj.trol - emacs@hsc24.mtk.nao.ac.jp

File Edit Options Buffers Tools Help

```
Number of cycles          (*):2                 ! (0=synthesis)
Observed profiles         (*):profile.per     ! (cosi)
Stray light file             :                  ! (none=no stray light contam)
PSF file                     :ins_prof.psf      ! (none=no convolution with PSF)
Wavelength grid file      (s):wavelength.grid     ! (cosi)
Atomic parameters file       :lines.1           ! (none=DEFAULT LINES file)
Abundances file              :thevenin.t        ! (none=DEFAULT ABUNDANCES file)
Initial guess model 1     (*):avpenleq3.mod
Initial guess model 2        :
File containing gaussian     :muj.gaus          ! (DEFAULT: none)
Weight for Stokes I          :1                 ! (DEFAULT=1; 0=not inverted)
Weight for Stokes Q          :1                 ! (DEFAULT=1; 0=not inverted)
Weight for Stokes U          :1                 ! (DEFAULT=1; 0=not inverted)
Weight for Stokes V          :4,4                 ! (DEFAULT=1; 0=not inverted)
AUTOMATIC SELECT. OF NODES?  :                  ! (DEFAULT=0=no; 1=yes)
Nodes for temperature 1      :1,2
Nodes for electr. press. 1   :
Nodes for microturb. 1       :0
Nodes for magnetic field 1   :1
Nodes for LOS velocity 1     :1
Nodes for gamma 1            :0,1
Nodes for phi 1              :1
Invert macroturbulence 1?    :0                   ! (0 or blank=no, 1=yes)
Nodes for temperature 2      :1
Nodes for electr. press. 2   :0
Nodes for microturb. 2       :0
Nodes for magnetic field 2   :0,1
Nodes for LOS velocity 2     :0,1
Nodes for gamma 2            :1
Nodes for phi 2              :1
Invert macroturbulence 2?    :                  ! (0 or blank=no, 1=yes)
Invert filling factor?       :0                 ! (0 or blank=no, 1=yes)
Invert stray light factor?   :0                 ! (0 or blank=no, 1=yes)
Nodes for center of gaussian :0,1                 ! Only 1 allowed if gaussian
Nodes for width of gaussian  :1                ! only 0 or 1 allowed if gaussian
mu=cos (theta)               :0.84                ! (DEFAULT: mu=1. mu<0 => West)
Estimated S/N for I          :800               ! (DEFAULT: 1000)
Continuum contrast           :                  ! (DEFAULT: not used)
Tolerance for SVD            :                  ! (DEFAULT value: 1e-4)
Initial diagonal element     :                  ! (DEFAULT value: 1.e1)
Gas pressure at surface 1    :5.e3              ! (0 or blank=Pe boundary cond.
Gas pressure at surface 2    :5.e3              ! (0 or blank=Pe boundary cond.
Magnetic pressure term?      :0                 ! (0 or blank=no, 1=yes
```

--:-- muj.trol (Fundamental)--L10--All

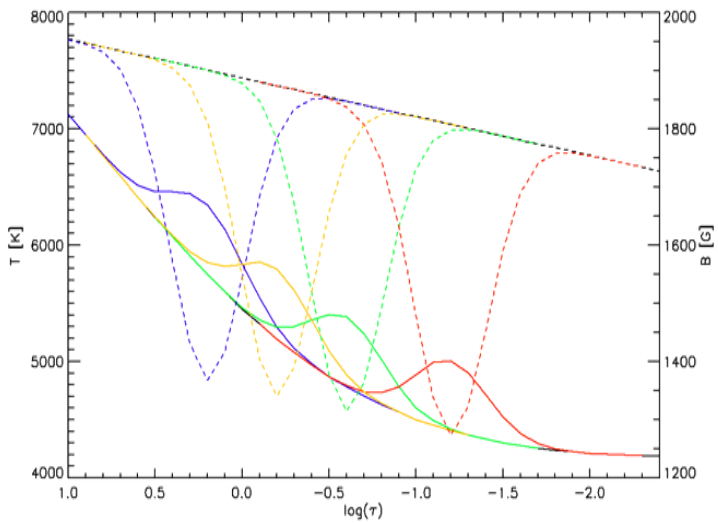
GAUSSIAN FILE

muj.gaus - emacs@hsc24.mtk.nao.ac.jp

File Edit Options Buffers Tools Help

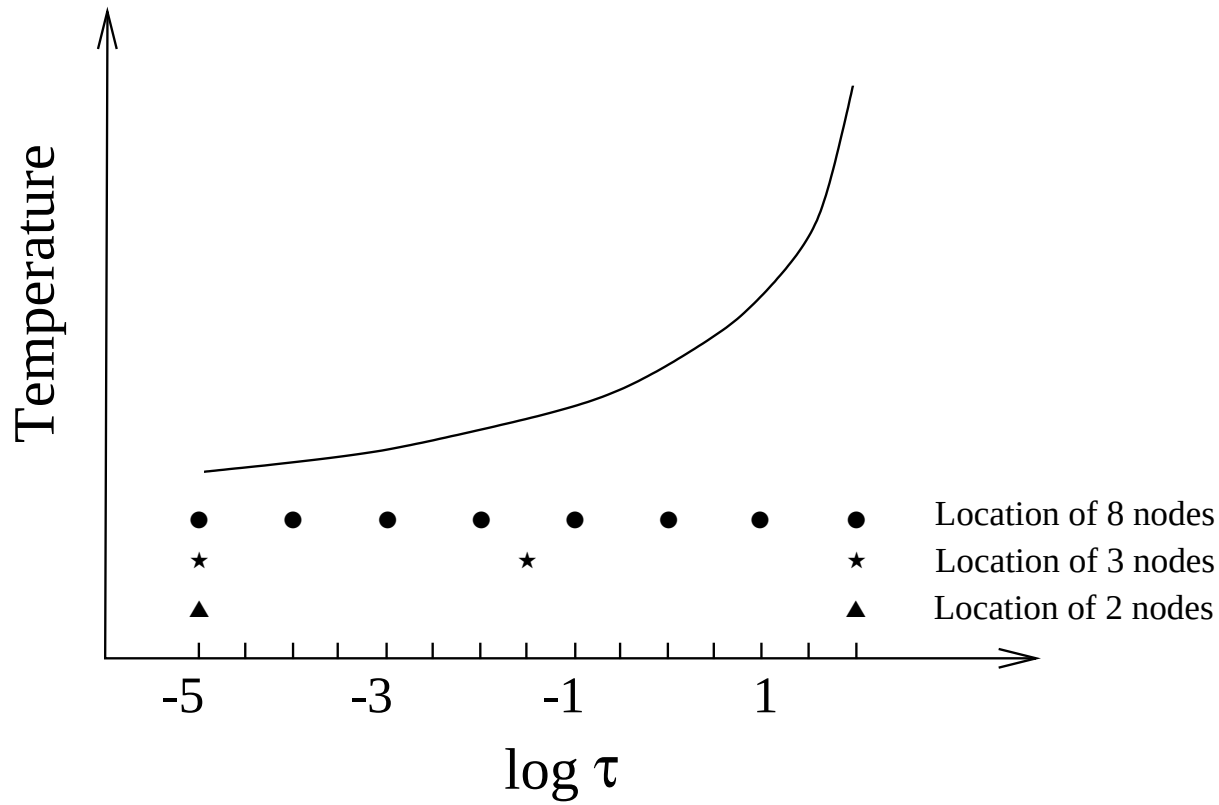
```
Central position index  :   0.2
Sigma (optical depth)   :   0.5
Amplitude for T         :   800.
Amplitude for vmic      :   -1.0E+05
Amplitude for B         :   -500.
Amplitude for v         :  -1.0E+05
Amplitude for gamma     :  -30.0
Amplitude for fi        :  -5.
```

--:-- muj.gaus (Fundamental)--L1--All



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

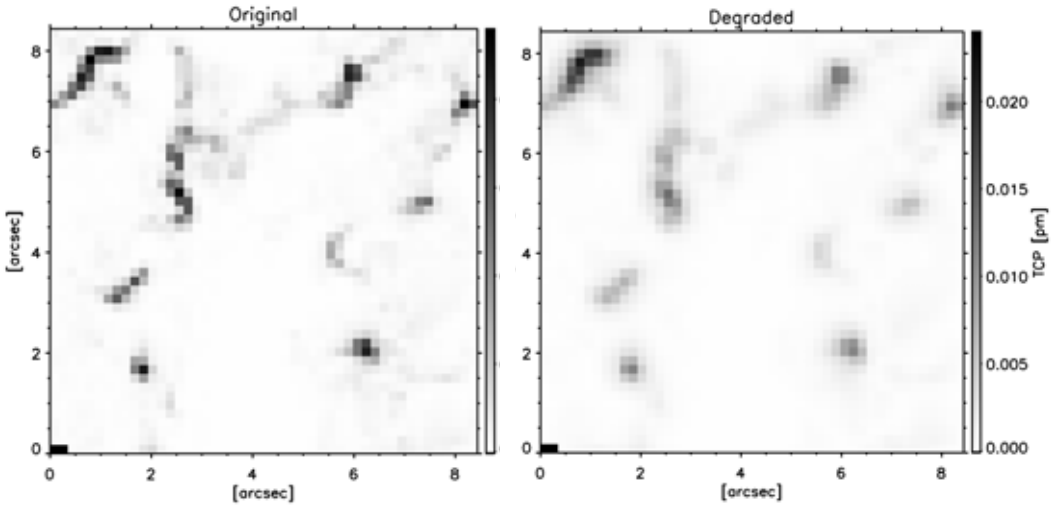


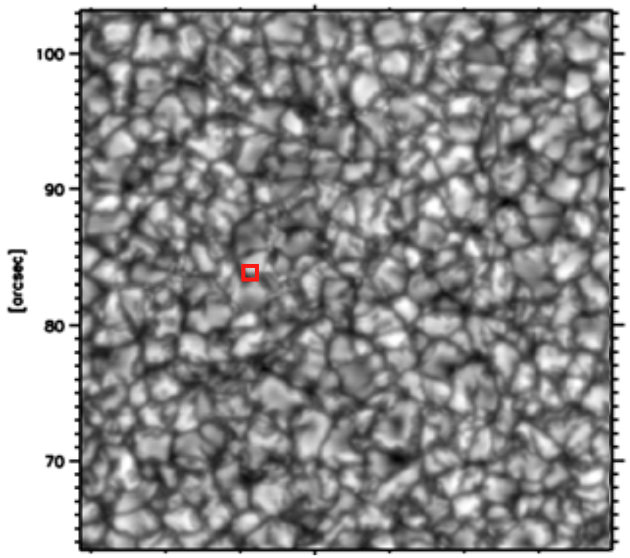
Stray-light considerations

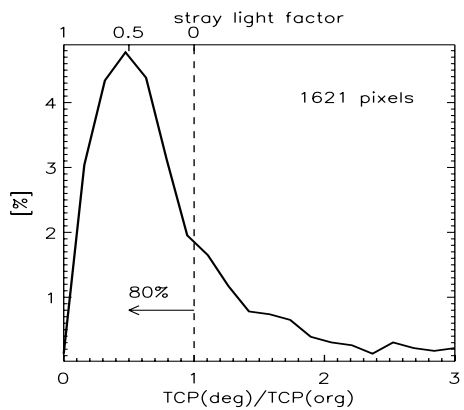
- Stray-light in ME inversions:
  - Equivalent to a magnetic filling factor f = 1- α
- Stray-light in SIR inversions:
  - It is NOT equivalent to a magnetic filling factor
  - In fact, SIR has two free parameters: α and f
- Global vs local stray-light profile
  - Classical treatment: global stray-light profile (over FOV)
  - Orozco Suárez et al. (2007): local stray-light profile accounts for telescope diffraction

Local stray light

- Telescope diffraction reduces the polarization signal
- Important for weak fields and noisy signals!







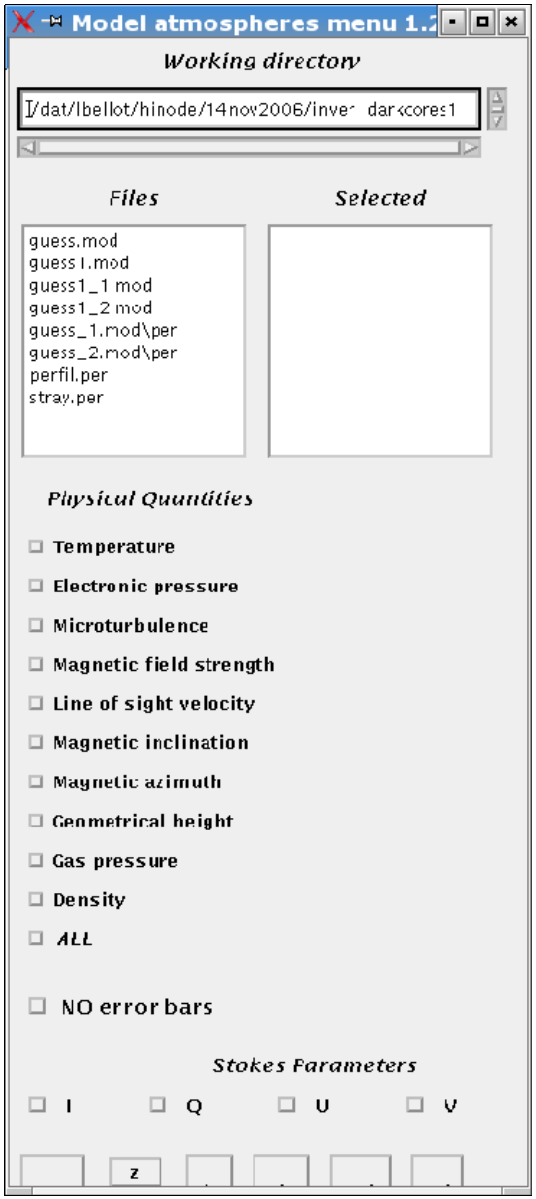
Unpolarized stray light

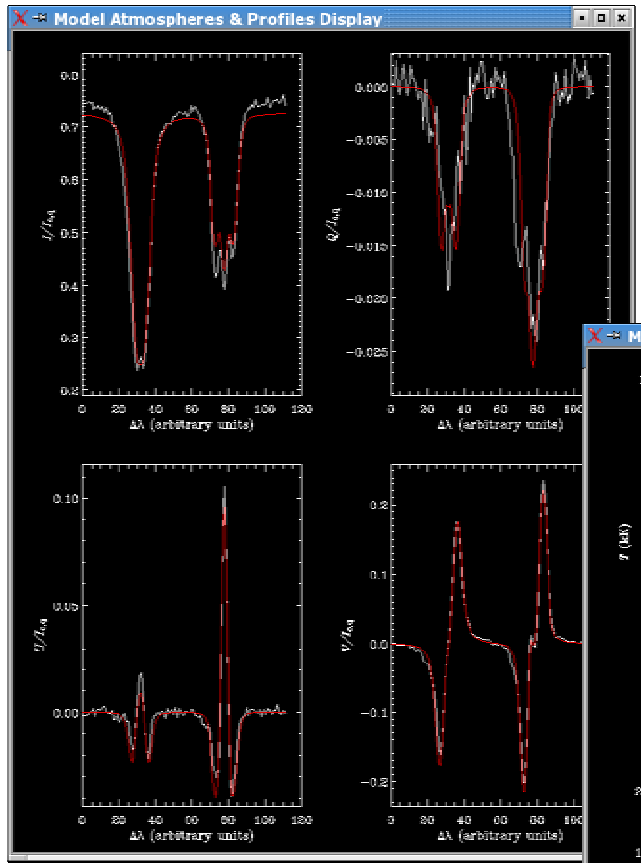
Average over a box 1″-wide centered on the pixel of interest

Executing the inversion

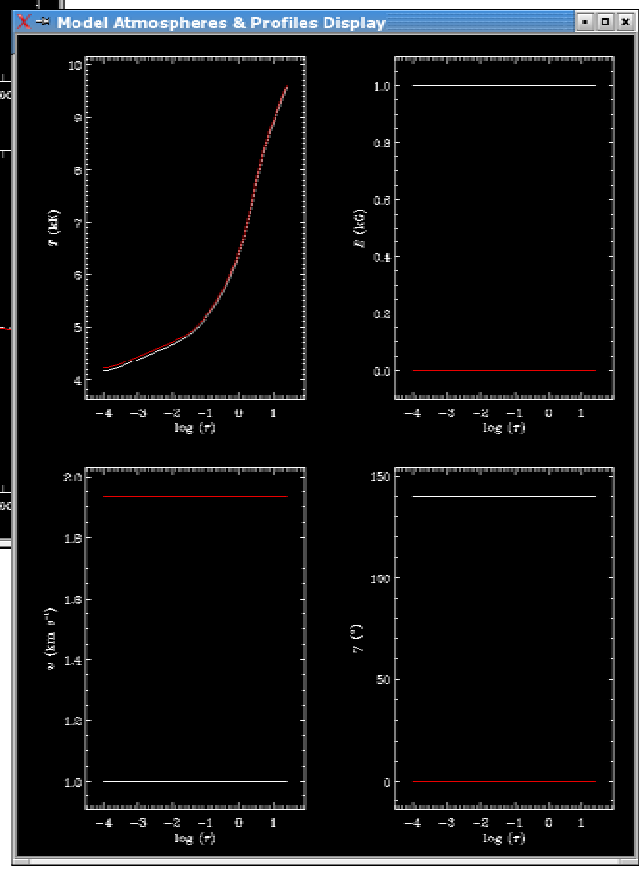
```
echo sir.trol | sir.x
```

Visualizing SIR results: graphics.pro





Stokes profiles



Model atmospheres