1st SolarNet school: Hands on sessions

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Overview

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1. Part I: 14:30-15:15
   - The SIR code
   - Synthetic spectra: effects of the magnetic field, temperature and gradients (area asymmetry)
2. Part II: 15:45-16:30
   - The SIR wrapper for MURAM simulations
   - Synthetic spectra: disk center & off-disk-center
3. Part III: Tuesday 13:30-14:15
   - Relationship: $\mathcal{C} - B_{\parallel}$ and $\mathcal{L} - B_{\perp}$
   - Relationship: $I_{c,630}$ and $I_{c,1565}$ with $T(\tau_c = 1)$
4. Part IV: Tuesday 14:30-15:15
   - Height of formation: response functions
   - Examples with semi-empirical models
5. Part V: Tuesday 15:45-16:30
   - Inversion of Stokes profiles
   - Examples with synthetic Stokes profiles

The SIR code

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- Ruiz Cobo & del Toro Iniesta (1992) ApJ, 398, 395
- Extremely popular and widely used code. More than 500 citations in ADS !
- Synthesis/Inversion code
- Written in Fortran 77
- Compile: make fc=gfortran sir.x
- Control file: sir.trol
- Running the code: echo sir.trol | ./sir.x
- In synthesis mode, SIR provides the theoretical Stokes profiles $\mathbf{I}(\lambda)$ given the physical parameters of an atmosphere as a function of the optical depth $\mathbf{X}(\tau_c)$

Control file: sir.trol

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Aug 19, 19 11:20 **sir.trol** Page 1/2

```
Number of cycles          (*):0                  ! (0=synthesis)
Observed profiles         (*):example.per        !
Stray light file             :                   ! (none=no stray light contam)
PSF file                     :                   ! (none=no convolution with PSF)
Wavelength grid file      (s):example.grid       ! (none=automatic selection)
Atomic parameters file       :LINES_example      ! (none=DEFAULT LINES file)
Abundances file              :THEVENIN           ! (none=DEFAULT ABUNDANCES file)
Initial guess model 1     (*):example.mod        !
Initial guess model 2        :
Weight for Stokes I          :                   ! (DEFAULT=1; 0=not inverted)
Weight for Stokes Q          :                   ! (DEFAULT=1; 0=not inverted)
```

a Cycles. 0 (synthesis), -1 (response functions), ≥ 1 (inversion)

b Output Stokes profiles: *.per

c Wavelength grid file: *.grid

d Atomic parameters file: LINES

e Abundances file: THEVENIN

f Atmospheric model file: *.mod

Element abundances: THEVENIN

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Apr 29, 14 14:23 **THEVENIN** Page 1/4

ABUNDANCES2

Abundances quoted by THEVENIN and taken from Grevesse, 1984, Physica Scripta, Vol.T8,49-58.
Abundances for Na,Mg,Al,Si,K,Ca,Sc,Ti,V,Cr,Mn,Fe,Co,Ni,Cu, Zn,Ge,Sr,Y,Zr,Nb,Mo,Ru,Rh,Ba,La,Ce,Pr,Nd,Sm,Eu,Gd,Dy,W and Ir from Holweger as quoted by Thevenin, 1989, Astron. Astrophys. Suppl.Ser 77, 137-154.

Atom	Abundance
1	12.00
2	11.00
3	1.00
4	1.15
5	2.60
6	8.69
7	7.99
8	8.91
9	4.56
10	8.00
11	6.28
12	7.53
13	6.43
14	7.50
15	5.45
16	7.21
17	5.50
18	6.58
19	5.05
20	6.36
21	2.99
22	4.88
23	3.91

Saturday A[illegible]t 17, 2019 THEVENIN 1/4

a atomic number Z

b element abundance $A_i = \log \frac{n_i}{n_{\rm H}} + 12$

c Grevesse (1984) Phys.Scrip, 78, 49 ; Thévenin (1989) A&AS, 77, 137 ; More recent: Grevesse et al. (2005) 17, 21

Spectral lines atomic parameters: LINES

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Aug 17, 19 23:27 **LINES_example** Page 1/1

a	b		c	d	e	f	
1=FE 1	6301.5012	1.0	3.654	-0.718	5P 2.0- 5D 2.0	0.243	2.353e-14
2=FE 1	6302.4936	1.0	3.686	-1.165	5P 1.0- 5D 0.0	0.241	2.397e-14
3=FE 1	15648.5150	1.0	5.426	-0.669	7D 1.0- 7D 1.0	0.229	2.729e-14
4=FE 1	15662.0180	1.0	5.830	0.190	5F 5.0- 5F 4.0	0.240	3.352e-14

(a) Line # + Element + Ionization stage ($1 = \text{neutral}$)

(b) Laboratory wavelength λ_0 (Å)

(c) Lower level ionization potential χ_{low} (eV)

(d) Oscillator strength $\log(gf)$

(e) Lower/Upper level electronic configuration: $(2S+1)$-L-J $\Rightarrow$ e.g. 5F 5.0 $\Rightarrow$ S=2; L=4 (F); J=5

(f) Collisional broadening parameters. Temperature exponent α & cross section σ (cm^{-2}). Aanste & O'Mara (1995), Barklem & O'Mara (1997), Barklem et al. (1998).

Spectral lines atomic parameters: LINES

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Where to get the atomic data you need ?

- National Institute for Standards and Technology (NIST): `https://physics.nist.gov/PhysRefData/ASD/lines_form.html` (Very reliable)
- Vienna Atomic Lines Database (VALD): `http://vald.astro.univie.ac.at/~vald3/php/vald.php` (Not very reliable, very extensive)
- Nave et al. (1994), ApJS, 94, 221 (Only Fe, very reliable, very extensive, no $\log(gf)$)
- Determined by fitting the solar spectrum: Thévenin (1989, 1990), Borrero et al. (2003)

Wavelength grid: *.grid

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Aug 19, 19 11:23 **example.grid** Page 1/1

a	b	c	d
1,2:	-500.00,	25.000,	1750.00
3:	-2000.00,	40.000,	2000.00
4:	-2000.00,	40.000,	2000.00

(a) Line # (see LINES file). For blended lines use commas, e.g. 1, 2

(b) Initial wavelength from λ_0 (mÅ)

(c) Wavelength step (mÅ)

(d) Final wavelength from λ_0 (mÅ)

Atmospheric model file: *.mod

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Aug 19, 19 11:10 **model.mod** Page 1/2

```
 0.1  0.0  0.0
 1.4000   6780.1  3.37281E+02  0.000E+00  3.6400E+03  2.4620E+05  5.2000E+01  5.2000E+01 -1.3218E+02  9.3327E+05  2.1563E-06
 1.3000   6536.0  2.18546E+02  0.000E+00  3.5400E+03  2.4290E+05  5.1500E+01  5.1500E+01 -1.2334E+02  8.8155E+05  2.1130E-06
 1.2000   6291.9  1.42426E+02  0.000E+00  3.4[illegible]E+03  2.[illegible]E+05  5.[illegible]E+01  5.1[illegible]E+01 -1.1[illegible]E+02  8.[illegible]E+05  2.0[illegible]E-06
 1.1000   6048.5  9.53289E+01  0.000E+00  3.[illegible]E+03  2.[illegible]E+05  5.[illegible]E+01  5.[illegible]E+01 -1.[illegible]E+02  7.[illegible]E+05  1.[illegible]E-06
 1.0000   5806.5  6.69004E+01  0.000E+00  3.2[illegible]E+03  2.[illegible]E+05  5.[illegible]E+01  5.0[illegible]E+01 -9.2[illegible]E+01  7.[illegible]E+05  1.9[illegible]E-06
 0.9000   5569.5  4.94006E+01  0.000E+00  3.1900E+03  2.2970E+05  4.9500E+01  4.9500E+01 -8.1397E+01  6.5384E+05  1.8391E-06
 0.8000   5340.7  3.74555E+01  0.000E+00  3.1100E+03  2.2640E+05  4.9000E+01  4.9000E+01 -7.1261E+01  6.0365E+05  1.7707E-06
 0.7000   5117.3  2.81571E+01  0.000E+00  3.0500E+03  2.2310E+05  4.8500E+01  4.8500E+01 -6.1896E+01  5.5892E+05  1.7111E-06
 0.6000   4902.9  2.06245E+01  0.000E+00  2.9900E+03  2.1980E+05  4.8000E+01  4.8000E+01 -5.3152E+01  5.1854E+05  1.6569E-06
 0.5000   4700.4  1.46772E+01  0.000E+00  2.9400E+03  2.1650E+05  4.7500E+01  4.7500E+01 -4.4754E+01  4.8101E+05  1.6032E-06
 0.4000   4513.9  1.02694E+01  0.000E+00  2.8900E+03  2.1320E+05  4.7000E+01  4.7000E+01 -3.6423E+01  4.4506E+05  1.5446E-06
 0.3000   4342.3  7.13996E+00  0.000E+00  2.8500E+03  2.0990E+05  4.6500E+01  4.6500E+01 -2.7919E+01  4.0984E+05  1.4786E-06
 0.2000   4188.8  5.02991E+00  0.000E+00  2.8100E+03  2.0660E+05  4.6000E+01  4.6000E+01 -1.9069E+01  3.7491E+05  1.4022E-06
 0.1000   4053.4  3.63176E+00  0.000E+00  2.7800E+03  2.0330E+05  4.5500E+01  4.5500E+01 -9.7689E+00  3.4030E+05  1.3152E-06
 0.0000   3940.5  2.72950E+00  0.000E+00  2.7500E+03  2.0000E+05  4.5000E+01  4.5000E+01  0.0000E+00  3.0641E+05  1.2182E-06
-0.1000   3854.0  2.15001E+00  0.000E+00  2.7300E+03  1.9670E+05  4.4500E+01  4.4500E+01  1.0152E+01  2.7398E+05  1.1137E-06
-0.2000   3785.0  1.74504E+00  0.000E+00  2.7100E+03  1.9340E+05  4.4000E+01  4.4000E+01  2.0568E+01  2.4369E+05  1.0086E-06
-0.3000   3726.8  1.44063E+00  0.000E+00  2.6900E+03  1.9010E+05  4.3500E+01  4.3500E+01  3.1179E+01  2.1584E+05  9.0731E-07
-0.4000   3676.7  1.20329E+00  0.000E+00  2.6800E+03  1.8680E+05  4.3000E+01  4.3000E+01  4.1948E+01  1.9048E+05  8.1160E-07
-0.5000   3633.6  1.01458E+00  0.000E+00  2.6700E+03  1.8350E+05  4.2500E+01  4.2500E+01  5.2850E+01  1.6756E+05  7.2243E-07
-0.6000   3597.9  8.64059E-01  0.000E+00  2.6600E+03  1.8020E+05  4.2000E+01  4.2000E+01  6.3854E+01  1.4701E+05  6.4013E-07
-0.7000   3564.7  7.37331E-01  0.000E+00  2.6500E+03  1.7690E+05  4.1500E+01  4.1500E+01  7.4948E+01  1.2868E+05  5.6554E-07
-0.8000   3534.9  6.31281E-01  0.000E+00  2.6500E+03  1.7360E+05  4.1000E+01  4.1000E+01  8.6141E+01  1.1237E+05  4.9801E-07
-0.9000   3511.6  5.45105E-01  0.000E+00  2.6500E+03  1.7030E+05  4.0500E+01  4.0500E+01  9.7420E+01  9.7921E+04  4.3685E-07
-1.0000   3498.0  4.77614E-01  0.000E+00  2.6500E+03  1.6700E+05  4.0000E+01  4.0000E+01  1.0873E+02  8.5235E+04  3.8173E-07
```

a b c d e f g h i j k l

(a) macroturbulent velocity $v_{\rm mac}$ (km s^{-1}), filling factor, straylight factor. Keep all this to 0.0,0.0,0.0.

(b) Optical depth scale at 500 nm (c) temperature T (K)

(d) electron pressure P_e (dyn cm^{-2})

(e) microturbulent velocity $v_{\rm mic}$ (cm s^{-1}). Keep at 0.0

(f) magnetic field strength B (Gauss)

Atmospheric model file: *.mod

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(b) Optical depth scale at 500 nm: $\log \tau_5$. Max ≥ 1.0

- If we are only interested in the Photosphere: min[$\log \tau_5 \approx -4$]
- If we want to include the Chromosphere: min[$\log \tau_5 \approx -7$]
- Chromosphere however is NLTE, so better don't use vanilla SIR)
- For NTLE better use NICOLE (Socas-Navarro et al. 2015)

Atmospheric model file: *.mod

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Aug 19, 19 11:10 **model.mod** Page 1/2

a	b	c	d	e	f	g	h	i	j	k	l
0.1 0.0 0.0											
1.4000	6780.	3.37281E+02	0.000E+00	3.6400E+03	2.4620E+05	5.2000E+01	5.2000E+01	-1.3218E+02	9.3327E+05	2.1563E-06	
1.3000	6536.0	2.18546E+02	0.000E+00	3.5400E+03	2.4290E+05	5.1500E+01	5.1500E+01	-1.2334E+02	8.8155E+05	2.1130E-06	
1.2000	6291.9	1.42426E+02	0.000E+00	3.4 E+03	2.3 E+05	5.1 E+01	5.1 E+01	-1.1 E+02	8.3 E+05	2.0 E-06	
1.1000	6048.5	9.53289E+01	0.000E+00	3.3 E+03	2.2 E+05	5.0 E+01	5.0 E+01	-1.0 E+02	7.8 E+05	1.9 E-06	
1.0000	5806.5	6.69004E+01	0.000E+00	3.2 E+03	2.1 E+05	5.0 E+01	5.0 E+01	-9.2 E+01	7.3 E+05	1.9 E-06	
0.9000	5569.5	4.94006E+01	0.000E+00	3.1900E+03	2.2970E+05	4.9500E+01	4.9500E+01	-8.1397E+01	6.5384E+05	1.8391E-06	
0.8000	5340.7	3.74555E+01	0.000E+00	3.1100E+03	2.2640E+05	4.9000E+01	4.9000E+01	-7.1261E+01	6.0365E+05	1.7707E-06	
0.7000	5117.3	2.81571E+01	0.000E+00	3.0500E+03	2.2310E+05	4.8500E+01	4.8500E+01	-6.1896E+01	5.5892E+05	1.7111E-06	
0.6000	4902.9	2.06245E+01	0.000E+00	2.9900E+03	2.1980E+05	4.8000E+01	4.8000E+01	-5.3152E+01	5.1854E+05	1.6569E-06	
0.5000	4700.4	1.46772E+01	0.000E+00	2.9400E+03	2.1650E+05	4.7500E+01	4.7500E+01	-4.4754E+01	4.8101E+05	1.6032E-06	
0.4000	4513.9	1.02694E+01	0.000E+00	2.8900E+03	2.1320E+05	4.7000E+01	4.7000E+01	-3.6423E+01	4.4506E+05	1.5446E-06	
0.3000	4342.3	7.13996E+00	0.000E+00	2.8500E+03	2.0990E+05	4.6500E+01	4.6500E+01	-2.7919E+01	4.0984E+05	1.4786E-06	
0.2000	4188.8	5.02991E+00	0.000E+00	2.8100E+03	2.0660E+05	4.6000E+01	4.6000E+01	-1.9069E+01	3.7491E+05	1.4022E-06	
0.1000	4053.4	3.63176E+00	0.000E+00	2.7800E+03	2.0330E+05	4.5500E+01	4.5500E+01	-9.7689E+00	3.4030E+05	1.3152E-06	
0.0000	3940.5	2.72950E+00	0.000E+00	2.7500E+03	2.0000E+05	4.5000E+01	4.5000E+01	0.0000E+00	3.0641E+05	1.2182E-06	
-0.1000	3854.0	2.15001E+00	0.000E+00	2.7300E+03	1.9670E+05	4.4500E+01	4.4500E+01	1.0152E+01	2.7398E+05	1.1137E-06	
-0.2000	3785.0	1.74504E+00	0.000E+00	2.7100E+03	1.9340E+05	4.4000E+01	4.4000E+01	2.0568E+01	2.4369E+05	1.0086E-06	
-0.3000	3726.8	1.44063E+00	0.000E+00	2.6900E+03	1.9010E+05	4.3500E+01	4.3500E+01	3.1179E+01	2.1584E+05	9.0731E-07	
-0.4000	3676.7	1.20329E+00	0.000E+00	2.6800E+03	1.8680E+05	4.3000E+01	4.3000E+01	4.1948E+01	1.9048E+05	8.1160E-07	
-0.5000	3633.6	1.01458E+00	0.000E+00	2.6700E+03	1.8350E+05	4.2500E+01	4.2500E+01	5.2850E+01	1.6756E+05	7.2243E-07	
-0.6000	3597.9	8.64059E-01	0.000E+00	2.6600E+03	1.8020E+05	4.2000E+01	4.2000E+01	6.3854E+01	1.4701E+05	6.4013E-07	
-0.7000	3564.7	7.37331E-01	0.000E+00	2.6500E+03	1.7690E+05	4.1500E+01	4.1500E+01	7.4948E+01	1.2868E+05	5.6554E-07	
-0.8000	3534.9	6.31281E-01	0.000E+00	2.6500E+03	1.7360E+05	4.1000E+01	4.1000E+01	8.6141E+01	1.1237E+05	4.9801E-07	
-0.9000	3511.6	5.45105E-01	0.000E+00	2.6500E+03	1.7030E+05	4.0500E+01	4.0500E+01	9.7420E+01	9.7921E+04	4.3685E-07	
-1.0000	3498.0	4.77614E-01	0.000E+00	2.6500E+03	1.6700E+05	4.0000E+01	4.0000E+01	1.0873E+02	8.5235E+04	3.8173E-07	

- (g) line-of-sight velocity $v_{\rm los}$ (cm s^{-1})
- (h) magnetic field inclination $\gamma \in [0, 180]$ (deg).
- (i) magnetic field azimuth $\varphi \in [0, 360]$ (deg).
- (j) geometrical height z (cm)
- (k) gas pressure P_g (dyn cm^{-2})
- (l) density ρ (g cm^{-3})

Output Stokes profiles: *.per

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Aug 19, 19 11:23 **example.per** Page 1/9

a	b	c	d	e	f
1	-500.0000	0.1105267E+00	-0.7525405E-05	0.5656670E-04	0.8102409E-03
1	-475.0000	0.1101560E+00	-0.9590532E-05	0.6655953E-04	0.9180262E-03
1	-450.0000	0.1097298E+00	-0.1223595E-04	0.7899398E-04	0.1046124E-02
1	-425.0000	0.1092410E+00	-0.1584250E-04	0.9414705E-04	0.1198438E-02
1	-400.0000	0.1086756E+00	-0.2055583E-04	0.1130847E-03	0.1380775E-02
1	-375.0000	0.1080181E+00	-0.2701625E-04	0.1365121E-03	0.1600735E-02
1	-350.0000	0.1072478E+00	-0.3562259E-04	0.1660742E-03	0.1867671E-02
1	-325.0000	0.1063386E+00	-0.4746583E-04	0.2031303E-03	0.2194496E-02
1	-300.0000	0.1052568E+00	-0.6342192E-04	0.2503230E-03	0.2597148E-02
1	-275.0000	0.1039586E+00	-0.8532387E-04	0.3101554E-03	0.3098018E-02

(a) Line # (see LINES file)
(b) $\lambda - \lambda_0$ (see *.grid file)
(c) Stokes $I/I_{c,qs}$
(d) Stokes $Q/I_{c,qs}$
(e) Stokes $U/I_{c,qs}$
(f) Stokes $V/I_{c,qs}$

$I_{c,qs}$ is the quiet Sun continuum intensity

Some examples & excercises

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- Compile sir source and move executable sir.x into synthesis_examples/ directory.
- Run SIR (echo | sir.trol ./sir.x) using three different atmospheric models: example1.mod, example2.mod & example3.mod
- Make sure the output Stokes profiles go to: example1.per, example2.per & example3.per
- Plot input atmospheres and output Stokes profile using python: import sir_utils as su, su.plot_atm('dir','file.mod'), su.plot_sto('dir','file.per')
- SIR source files located in /sir/src/
- SIR example files located in /sir/synthesis_examples/
- Python files located in python/

Some examples & excercises

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These examples mimic the simple analytical solutions we saw study earlier:

- example1.mod: $\gamma = 0 \Rightarrow Q, U = 0$
- example2.mod: $\gamma = 90$, $\varphi = 0 \Rightarrow V, U = 0$
- example3.mod: $\gamma = 90$, $\varphi = 45 \Rightarrow V, Q = 0$

Stokes V area asymmetry

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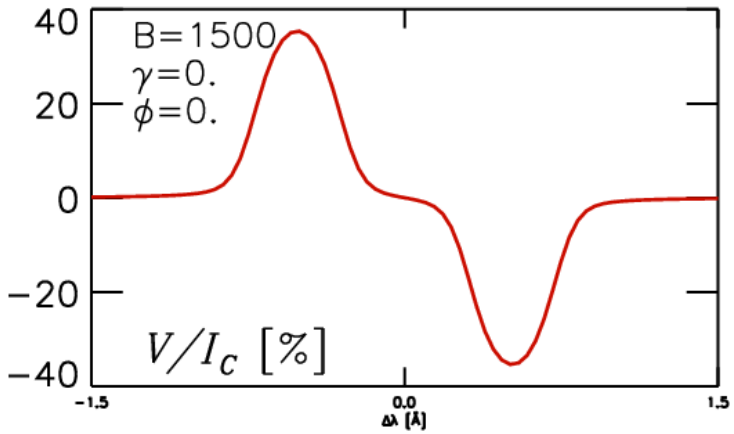

In normal circumstances Stokes V is perfectly antisymmetric: $V(\lambda - \lambda_0) = -V(\lambda_0 - \lambda)$, meaning:

$$\mathrm{d}A \stackrel{\mathrm{def}}{=} \int_{-\infty}^{\infty} V(\lambda)\mathrm{d}\lambda = 0 \qquad (1)$$

Landolfi & Landi Degl'Innocenti (1996) show that $\mathrm{d}v_{\mathrm{los}}/\mathrm{d}\tau_c \neq 0 \iff \mathrm{d}A \neq 0$

Stokes V area asymmetry

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Solanki & Pahlke (1988) show that:

$$\mathrm{sign}(\mathrm{d}A) = -\mathrm{sign}\left(\frac{\mathrm{d}v_{\mathrm{los}}}{\mathrm{d}\tau_c}\frac{\mathrm{d}\|B\|}{\mathrm{d}\tau_c}\right) \qquad (2)$$

Let us test this expression:

- Run sir using three different atmospheric models: example4.mod, example5.mod & example6.mod
- Output Stokes profiles: example4.per, example5.per, example6.per
- Plot input atmospheres and output Stokes profile using python: import sir_utils as su, su.plot_atm('dir','file.mod'), su.plot_sto('dir','file.per')
- Calculate area asymmetry in output Stokes V profiles using python: su.asymm('dir','file.per')

Stokes V area asymmetry

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- Prediction for example4.mod:

$$\frac{\mathrm{d}\|B\|}{\mathrm{d}\tau_c} \approx \frac{B(\tau_c = 1) - B(\tau_c = 10^{-3})}{1 - 10^{-3}} = \frac{2340 - 740}{0.999} > 0$$

$$\frac{\mathrm{d}v_{\mathrm{los}}}{\mathrm{d}\tau_c} \approx \frac{v_{\mathrm{los}}(\tau_c = 1) - v_{\mathrm{los}}(\tau_c = 10^{-3})}{1 - 10^{-3}} = \frac{4.6 - 0.6}{0.999} > 0$$

Therefore, according to Eq.(2): $\mathrm{d}A < 0$!!

- Prediction for example5.mod:

$$\frac{\mathrm{d}\|B\|}{\mathrm{d}\tau_c} < 0 \; ; \frac{\mathrm{d}v_{\mathrm{los}}}{\mathrm{d}\tau_c} > 0 \; ; \mathrm{d}A > 0$$

- Prediction for example6.mod:

$$\frac{\mathrm{d}\|B\|}{\mathrm{d}\tau_c} < 0 \; ; \frac{\mathrm{d}v_{\mathrm{los}}}{\mathrm{d}\tau_c} < 0 \; ; \mathrm{d}A < 0$$

Stokes V area asymmetry

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- Prediction of $\mathrm{d}A$ according to Eq.(2) holds much better for visible (Fe I 630 nm lines) than near-IR lines (Fe I 1565 nm) lines.
- $\mathrm{d}A$ in near-infrared lines is heavily influenced by $\mathrm{d}\varphi/\mathrm{d}\tau_c$, which is neglected in Eq.(2).
- All possible effects: $\mathrm{d}B/\mathrm{d}\tau_c$, $\mathrm{d}\gamma/\mathrm{d}\tau_c$, $\mathrm{d}\varphi/\mathrm{d}\tau_c$, $\mathrm{d}v_{\mathrm{los}}/\mathrm{d}\tau_c$ are explained in Landolfi & Landi Degl'Innocenti (1996) and Müller et al. (2002)

Effects of the temperature

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- For simplicity let us consider $B_{\rm ext} = 0 \Rightarrow$ $Q, U, V = 0$. We look only at Stokes I
- SIR code normalizes intensities to the quiet Sun continuum intensity $I_{\rm c,qs}$ as obtained by the HSRA model (Gingerich et al. 1971)
- Continuum intensity mimics the temperature at $\tau_5 = 1$
  - If $T(\tau_5 = 1) > T_{\rm hsra}(\tau_5 = 1) \approx 6390K \Rightarrow$ $I_{\rm c}/I_{\rm c,qs} > 1$
  - If $T(\tau_5 = 1) < T_{\rm hsra}(\tau_5 = 1) \approx 6390K \Rightarrow$ $I_{\rm c}/I_{\rm c,qs} < 1$
- Run SIR with example7.mod (HSRA), example8.mod & example9.mod
- In python: import sir_utils as su, su.oplot_tem_stokesi('dir','listatm','listper')

Effects of the temperature

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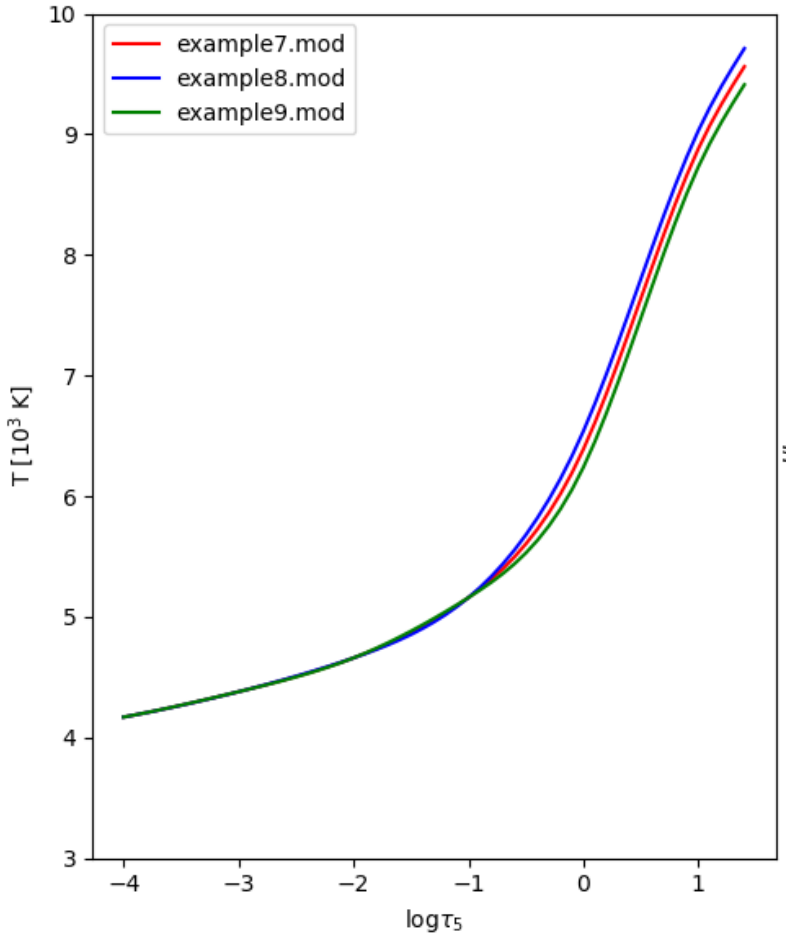

Effects of the temperature

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- Core intensity mimics the temperature at higher up, say i.e. $\tau_5 = 10^{-2} - 10{-}4$ (depends on the spectral line)
  - If $T(\tau_5 = 10^{-3}) > T_{\rm hsra}(\tau_5 = 10^{-3}) \approx 4380K \Rightarrow I_{\rm core}/I_{\rm c,qs} > 1$
  - If $T(\tau_5 = 10^{-3}) < T_{\rm hsra}(\tau_5 = 10^{-3}) \approx 4380K \Rightarrow I_{\rm c}/I_{\rm c,qs} < 1$
- Run SIR with example7.mod (HSRA), example10.mod & example11.mod.
- In python: Use import sir_utils as su, su.oplot_tem_stokesi ('dir','listatm','listper')

Effects of the temperature

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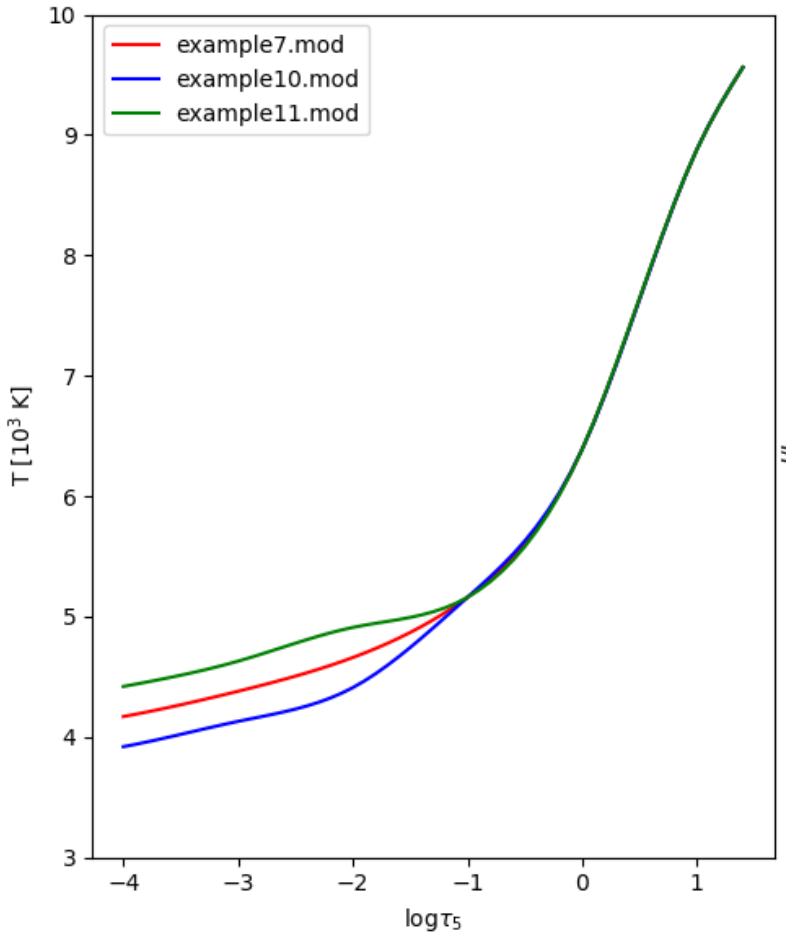

Effects of the temperature

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Let us see what we have learned. Can you predict how Stokes I will look like if ?

- $T(\tau_5) < T_{\rm hsra}(\tau_5)\ \forall\ \tau_5$: example12.mod
- $T(\tau_5) > T_{\rm hsra}(\tau_5)\ \forall\ \tau_5$: example13.mod
- $\mathrm{d}T/\mathrm{d}\tau_5 = -\mathrm{d}T_{\rm hsra}/\mathrm{d}\tau_5$: example14.mod
- Run SIR and compare example7 (HSRA) with example12,13,14.
- In python: Use import sir_utils as su, su.oplot_tem_stokesi ('dir','listatm','listper')

Effects of the temperature

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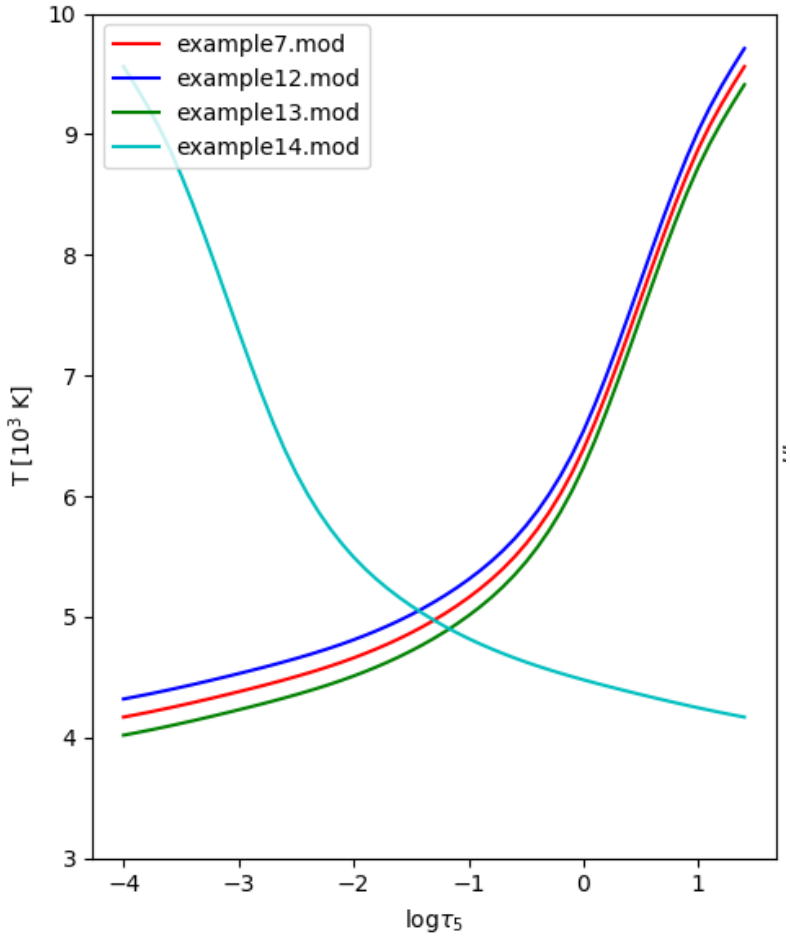

The Stok3d wrapper

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- Wrapper for SIR to produce synthetic Stokes profiles from MHD simulations
- Currently reads only MURaM simulations (Vögler et al. 2005, Rempel et al. 2009). If you want also CO5BOLD (Freytag et al. 2012) ask Flavio Calvo
- Written in Fortran 90 and parallelized with MPI
- Compile: make clean, make stok3d
- Parameter file: parameters.f90 $\Rightarrow$ recompile code when changed !
- Running the wrapper: mpirun -n # ./stok3d.x
- Stok3d takes physical parameters from simulations (x, y, z), coverts to (x, y, τ_5) (calculating opacities $\mathcal{K}_c$), writes atmospheres (*.mod) and performs synthesis using SIR.
- If using inclined line-of-sights ($\Theta \neq 0$) it determines new grid using trilinear interpolation.

Parameter file: parameters.f90

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Aug 26, 19 9:11 **parameters.f90** Page 1/1

```
MODULE PARAMETERS
  ! J M Borrero: Jun 16, 2009
  ! Adapted from muram stokes
  CHARACTER*200,      PARAMETER     :: BINARY='sir.x'
  CHARACTER*200,      PARAMETER     :: FILE_GRID='example.grid'
  CHARACTER*200,      PARAMETER     :: FILE_ATOM='LINES_example'
  CHARACTER*200,      PARAMETER     :: DIR_SYNTHESIS='./RUN_synth_1/'
  CHARACTER*200,      PARAMETER     :: DIR_SIR='./SIR_files/'
  CHARACTER*200,      PARAMETER     :: DIR_INPUT='../mhd_cube/'
  CHARACTER*200,      PARAMETER     :: DIR_OUTPUT_ATMOS='../atmos_theta0/'
  CHARACTER*200,      PARAMETER     :: DIR_OUTPUT_STOK='../profiles_theta0/'
  CHARACTER*200,      PARAMETER     :: PRES_FILE='pres_f90_nx256_ny256_nz192.dat'
  CHARACTER*200,      PARAMETER     :: TEMP_FILE='temp_f90_nx256_ny256_nz192.dat'
  CHARACTER*200,      PARAMETER     :: DENS_FILE='dens_f90_nx256_ny256_nz192.dat'
  CHARACTER*200,      PARAMETER     :: VXX_FILE=''
  CHARACTER*200,      PARAMETER     :: VYY_FILE=''
  CHARACTER*200,      PARAMETER     :: VZZ_FILE=''
  CHARACTER*200,      PARAMETER     :: BXX_FILE='magx_f90_nx256_ny256_nz192.dat'
  CHARACTER*200,      PARAMETER     :: BYY_FILE='magy_f90_nx256_ny256_nz192.dat'
  CHARACTER*200,      PARAMETER     :: BZZ_FILE='magz_f90_nx256_ny256_nz192.dat'
  INTEGER,            PARAMETER     :: NX = 256
  INTEGER,            PARAMETER     :: NY = 256
  INTEGER,            PARAMETER     :: NZ = 192
  INTEGER,            PARAMETER     :: NZN = 5000
  REAL(4),            PARAMETER     :: DELTAX = 12D0  !KM
  REAL(4),            PARAMETER     :: DELTAY = 12D0  !KM
  REAL(4),            PARAMETER     :: DELTAZ = 8D0   !KM
  REAL(4),            PARAMETER     :: THETA = 0D0
  REAL(4),            PARAMETER     :: AZIM = 0.0D0
  LOGICAL,            PARAMETER     :: BOX_PMODE = .FALSE.
  LOGICAL,            PARAMETER     :: FORCE_HYDRO = .FALSE.
  LOGICAL,            PARAMETER     :: NEG_POLARITY = .FALSE.
  INTEGER,            PARAMETER     :: XINI=1
  INTEGER,            PARAMETER     :: XEND=256
  INTEGER,            PARAMETER     :: YINI=1
  INTEGER,            PARAMETER     :: YEND=256
  INTEGER                           :: LX, LY, LZ
END MODULE PARAMETERS
```

Monday August 26, 2019 parameters.f90 1/1

(a) SIR related files: executable (sir.x), wavelength grid (*.grid), atomic data (LINES*).

(b) Location of SIR files. In this directory there must be also abundances files (THEVENIN) and control file (sir.trol).

(c) Location of output atmospheres and synthetic Stokes profiles.

Parameter file: parameters.f90

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Aug 26, 19 9:11 **parameters.f90** Page 1/1

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  CHARACTER*200,      PARAMETER     :: DIR_SIR='./SIR_files/'
  CHARACTER*200,      PARAMETER     :: DIR_INPUT='../mhd_cube/'
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  CHARACTER*200,      PARAMETER     :: VYY_FILE=''
  CHARACTER*200,      PARAMETER     :: VZZ_FILE=''
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  INTEGER,            PARAMETER     :: NX = 256
  INTEGER,            PARAMETER     :: NY = 256
  INTEGER,            PARAMETER     :: NZ = 192
  INTEGER,            PARAMETER     :: NZN = 5000
  REAL(4),            PARAMETER     :: DELTAX = 12D0   !KM
  REAL(4),            PARAMETER     :: DELTAY = 12D0   !KM
  REAL(4),            PARAMETER     :: DELTAZ = 8D0    !KM
  REAL(4),            PARAMETER     :: THETA = 0D0
  REAL(4),            PARAMETER     :: AZIM = 0.0D0
  LOGICAL,            PARAMETER     :: BOX_PMODE = .FALSE.
  LOGICAL,            PARAMETER     :: FORCE_HYDRO = .FALSE.
  LOGICAL,            PARAMETER     :: NEG_POLARITY = .FALSE.
  INTEGER,            PARAMETER     :: XINI=1
  INTEGER,            PARAMETER     :: XEND=256
  INTEGER,            PARAMETER     :: YINI=1
  INTEGER,            PARAMETER     :: YEND=256
  INTEGER                           :: LX, LY, LZ
END MODULE PARAMETERS
```

Monday August 26, 2019 parameters.f90 1/1

(a) Location of the MHD simulation cubes.

(b) Files containing physical parameters from MHD simulations. Binary unformatted format.

(c) Sizes n_x,n_y,n_z of cubes.

(d) Sizes δx,δy,δz of grid cells.

Parameter file: parameters.f90

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Aug 26, 19 9:11 **parameters.f90** Page 1/1

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  CHARACTER*200,      PARAMETER     :: FILE_ATOM='LINES_example'
  CHARACTER*200,      PARAMETER     :: DIR_SYNTHESIS='./RUN_synthesis/'
  CHARACTER*200,      PARAMETER     :: DIR_SIR='./SIR_files/'
  CHARACTER*200,      PARAMETER     :: DIR_INPUT='../mhd_cube/'
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  CHARACTER*200,      PARAMETER     :: TEMP_FILE='temp_f90_nx256_ny256_nz192.dat'
  CHARACTER*200,      PARAMETER     :: DENS_FILE='dens_f90_nx256_ny256_nz192.dat'
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  CHARACTER*200,      PARAMETER     :: VYY_FILE=''
  CHARACTER*200,      PARAMETER     :: VZZ_FILE=''
  CHARACTER*200,      PARAMETER     :: BXX_FILE='magx_f90_nx256_ny256_nz192.dat'
  CHARACTER*200,      PARAMETER     :: BYY_FILE='magy_f90_nx256_ny256_nz192.dat'
  CHARACTER*200,      PARAMETER     :: BZZ_FILE='magz_f90_nx256_ny256_nz192.dat'
  INTEGER,            PARAMETER     :: NX = 256
  INTEGER,            PARAMETER     :: NY = 256
  INTEGER,            PARAMETER     :: NZ = 192
  INTEGER,            PARAMETER     :: NZN = 5000
  REAL(4),            PARAMETER     :: DELTAX = 12D0  !KM
  REAL(4),            PARAMETER     :: DELTAY = 12D0  !KM
  REAL(4),            PARAMETER     :: DELTAZ = 8D0   !KM
  REAL(4),            PARAMETER     :: THETA = 0D0
  REAL(4),            PARAMETER     :: AZIM = 0.0D0
  LOGICAL,            PARAMETER     :: BOX_PMODE = .FALSE.
  LOGICAL,            PARAMETER     :: FORCE_HYDRO = .FALSE.
  LOGICAL,            PARAMETER     :: NEG_POLARITY = .FALSE.
  INTEGER,            PARAMETER     :: XINI=1
  INTEGER,            PARAMETER     :: XEND=256
  INTEGER,            PARAMETER     :: YINI=1
  INTEGER,            PARAMETER     :: YEND=256
  INTEGER                           :: LX, LY, LZ
END MODULE PARAMETERS
```

Monday August 26, 2019 parameters.f90 1/1

(a) Number of points for re-interpolating atmospheres *NZN*. Remember that: reinterpolation is needed when using SIR because it solves the RTE in optical depth τ_c

(b) Θ: viewing angle with respect to z-axis in the simulation box. ϕ: viewing angle with respect to x-axis. Disk center: $\Theta = 0$, Limb: $\Theta \rightarrow 90^\circ$.

Synthesis of MHD cube at disk center: $\Theta = 0^\circ$

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- In parameters.f90 set $\Theta = 0$, $\phi = 0$.
- Output directories: atmos_theta0/, profiles_theta0/
- Compile: make clean & make stok3d and run mpirun -n # ./stok3d.x
- Check how files start to appear in output directories.
- It will take a few hours for a 256×256 cubes. You can do it at home or in a large computer.
- Here I have the final results for prepared: tar xvf atmos_theta0.tar.gz and tar xvf profiles_theta0.tar.gz files in output directories.

Synthesis of MHD cube at disk center: $\Theta = 0^\circ$

- From the physical parameters i.e T, B_x, B_y, etc as a function of (x, y, z) we produce synthetic Stokes vector $\mathbf{I}$ as a function of (x, y, λ)
- You can check individual Stokes profiles and atmosphere using sir_utils.plot_atm & sir_utils.plot_sto
- Here we are a bit more interested in spatial (x, y) properties:
- Continuum intensity: $I(x, y, \lambda_c)$
- Total linear $\mathcal{L}$ and circular $\mathcal{C}$ polarization:

$$\mathcal{C} = \int_{-\infty}^{\infty} \|V(x, y, \lambda)\| \mathrm{d}\lambda \quad (3)$$

$$\mathcal{L} = \int_{-\infty}^{\infty} \{Q(x, y, \lambda)^2 + U(x, y, \lambda)^2\}^{1/2} \mathrm{d}\lambda \quad (4)$$

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Synthesis of MHD cube at disk center: $\Theta = 0^\circ$

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- Do not confuse area asymmetry $\mathrm{d}A$-Eq.(1)- with total circular polarization $\mathcal{C}$-Eq(3)-.
- As a very rude approximation we can say: $\mathcal{C} \propto B_{\parallel} = B\cos\gamma$, $\mathcal{L} \propto B_{\perp} = B\sin\gamma$
- To plot results: import stok3d_utils as s3u & s3u.read_stok_cube('dir',x0,x1,y0,y1)

Synthesis of MHD cube at disk center: $\Theta = 0^\circ$

1st SolarNet school: Hands on sessions

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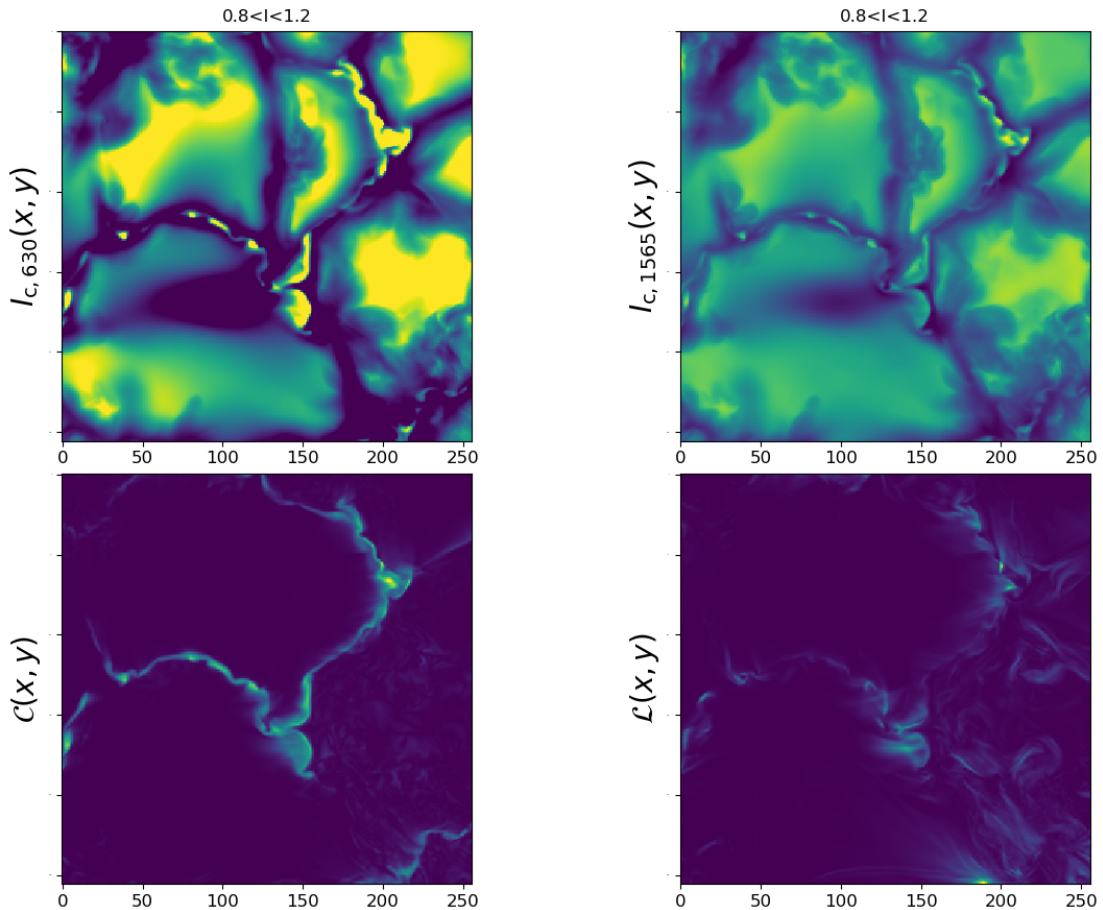

MHD cube off disk center: $\Theta = 30^\circ$

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- In parameters.f90 set $\Theta = 30$, $\phi = 0$
- Output directories: atmos_theta30/, profiles_theta30/
- Need to recompile $\Rightarrow$ make clean & make stok3d
- Run: mpirun -n # ./stok3d.x
- Check how files start to appear in output directories.
- Again it will take long to finish. Results are available already: tar xvf atmos_theta30.tar and tar xvf profiles_theta30.tar files in output directories.
- use stok3d_utils & read_stok_cube to plot results.
- Interpolation problems start to appear for $\Theta \geq 45^\circ$. Try not to go so far off the disk.

MHD cube off disk ceter: $\Theta = 30^\circ$

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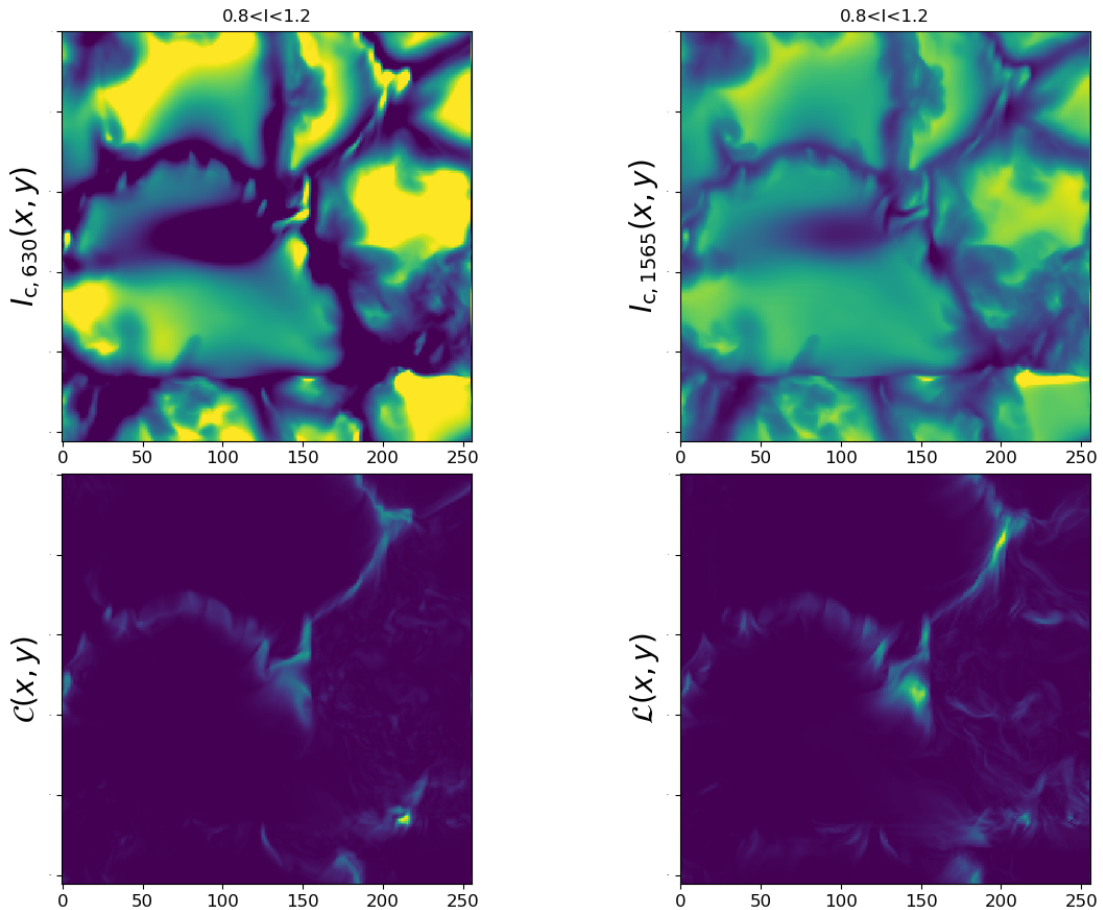

$\mathcal{L}$, $\mathcal{C}$, $B_\perp$, $B_\parallel$

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- If you remember from yesterday's lecture:

$$\begin{aligned} V &\approx \eta_V \propto \mathcal{F}(B)\cos\gamma \\ Q &\approx \eta_Q \propto \mathcal{F}(B)\sin\gamma\cos 2\varphi \\ U &\approx \eta_U \propto \mathcal{F}(B)\sin\gamma\sin 2\varphi \end{aligned}$$

- Therefore: $\mathcal{C}$ (Eq.3) $\Rightarrow$ proxy of $B\cos\gamma = B_\parallel$ (magnetic field parallel to the observer's line-of-sight)
- Likewise: $\mathcal{L}$ (Eq.4) $\Rightarrow$ proxy of $B\sin\gamma = B_\perp$ (magnetic field perpendicular to the observer's line of sight).
- Proxy is very accurate if $\mathcal{F}(B) \approx B$

$\mathcal{L}$, $\mathcal{C}$, $B_\perp$, $B_\parallel$

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- Let us test the previous idea: **additional excercise**
- Create your own program to read all 256×256 atmospheres and create $B_\parallel(x, y, \tau_5^\dagger)$ and $B_\perp(x, y, \tau_5^\dagger)$.
- Discuss and select an appropiate optical depth $\tau_5^\dagger$
- Compare those with $\mathcal{C}(x, y)$ and $\mathcal{L}(x, y) \Rightarrow$ scatter plot.
- If you need it, use: import stok3d_utils as s3u, s3u.check_bcl('diratm', 'dirstok',x0,x1,y0,y1,log τ_5)
- Discuss and select different optical depth, $\tau_5^\dagger$,to correlate $\mathcal{C}$ and $\mathcal{L}$ with $B_\parallel$ and $B_\perp$, respectively.

$\mathcal{L}$, $\mathcal{C}$, $B_\perp$, $B_\parallel$

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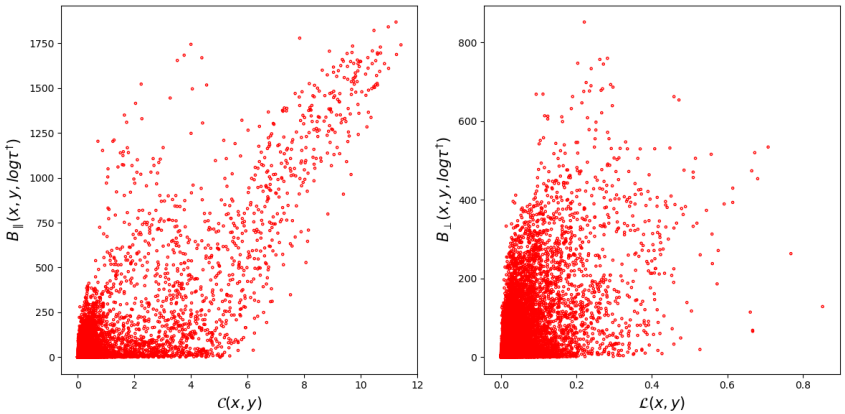
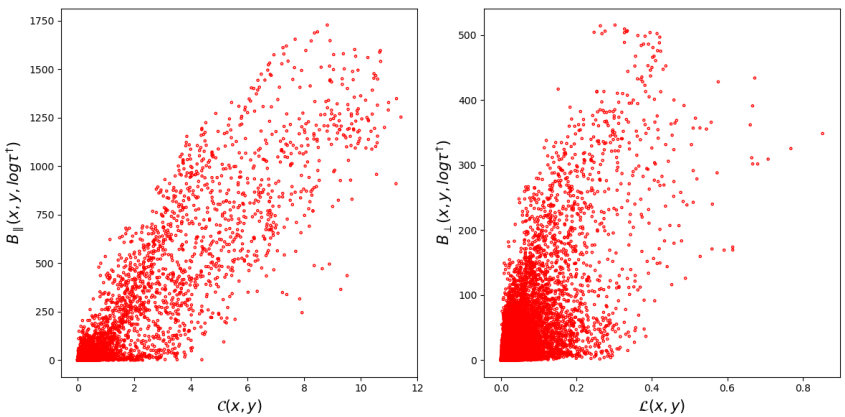
Example with: x0=100, x1=156, y0=1, y1=256, $\log \tau_5 = 0$



Example with: x=100, x=156, y=1, y=256, $\log \tau_5 = -1$



I_c vs $T(\tau_5 = 1)$

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- We have already seen (i.e. temperature effects) that the continuum intensity mimics the temperature at $\tau_5 = 1$
- Let us test this: **additional excercise**
- Create your own program to read all 256×256 atmospheres and create $T(x, y, \tau_5 = 1)$
- Compare it with $I_{c,\mathrm{vis}}$ & $I_{c,\mathrm{inf}} \Rightarrow$ scatter plot
- If you need it, use: import stok3d_utils as s3u, s3u.check_tem_ic('diratm', dirstok,x0,x1,y0,y1,log τ_5)
- Does the scatter plot correlate better with $I_{c,\mathrm{vis}}$ or $I_{c,\mathrm{inf}}$?
- Discuss and select different optical depth, $\tau_5^\dagger$,to correlate $T(\tau_5^\dagger)$ with $I_{c,\mathrm{vis}}$ or $I_{c,\mathrm{inf}}$

I_c vs $T(\tau_5 = 1)$

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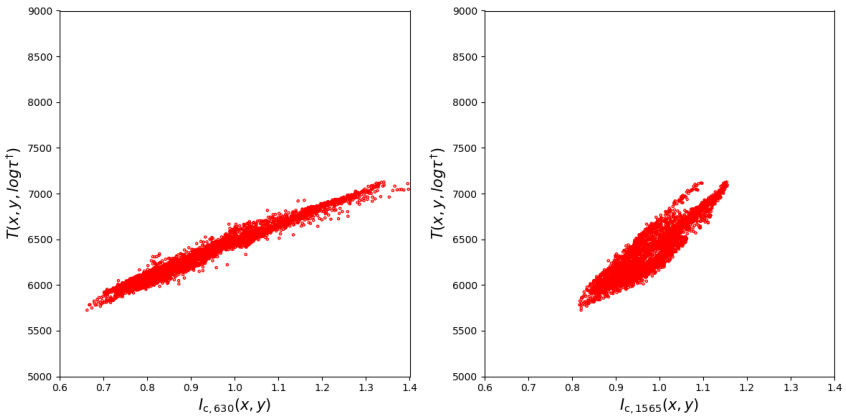
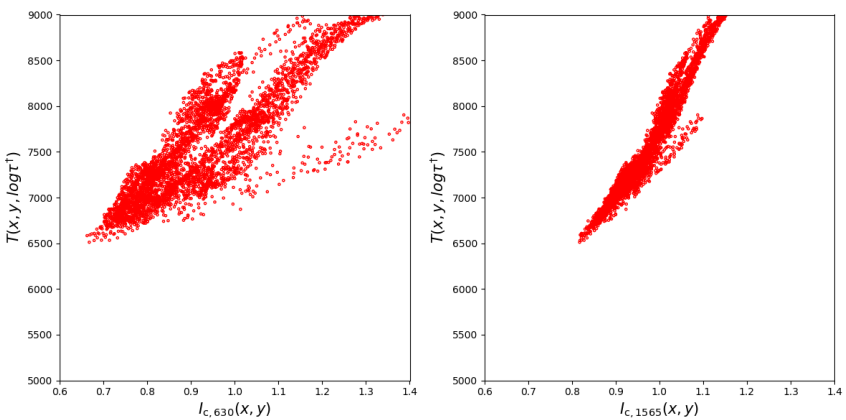
Example with: x0=120, x1=136, y=1, y=256, $\log \tau_5 = 0$
$\Rightarrow c_{\mathrm{vis,T}} = 0.958$; $c_{\mathrm{ir,T}} = 0.914$



Example with: x0=120, x1=136, y0=1, y1=256,
$\log \tau_5 = 0.5 \Rightarrow c_{\mathrm{vis,T}} = 0.825$; $c_{\mathrm{ir,T}} = 0.971$



I_c vs $T(\tau_5 = 1)$

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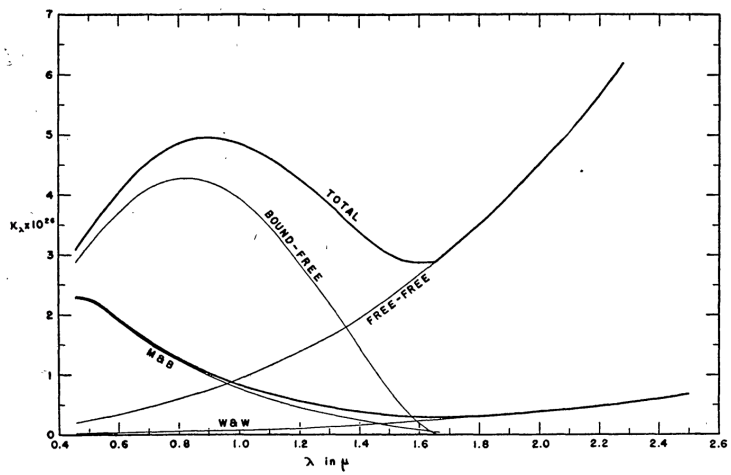
- H^- opacity is higher at 500 nm than at 1565 nm $\Rightarrow$ $\mathcal{K}_c$ is higher at 500 nm than at 1565 nm $\Rightarrow$ we see slighty deeper in the near-IR than in the visible:

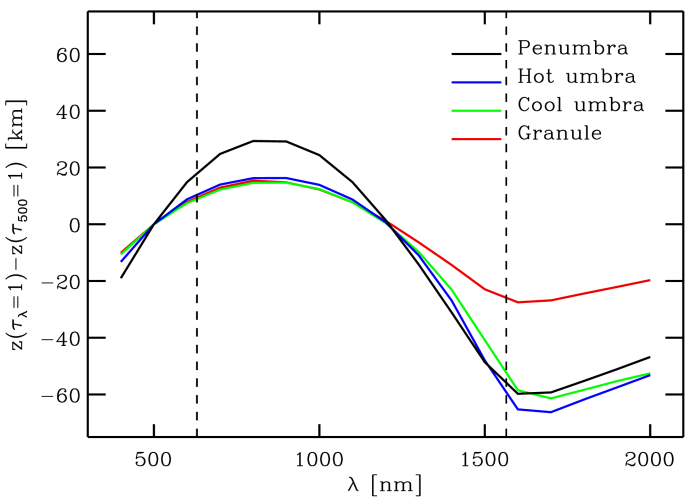
$$z(\log \tau_{1565} = 0) - z(\log \tau_{500} = 0) \approx 50 - 75 \quad \text{km}$$

- The $\tau_c = 1$-level at 1565 nm forms at around $\tau_c = 3$ at 500 nm

$$z(\log \tau_{1565} = 0) \approx z(\log \tau_{500} = 0.5)$$



Chandrasekhar & Breen (1946)



Borrero et al. (2016)

Definition of response funtions: $\mathcal{R}(\tau_c, \lambda)$

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Response functions are the partial derivatives of the Stokes vector with respect of the physical paramters:

$$\mathcal{R}_{\mathbf{I},\mathrm{X}}(\lambda, \tau_c) = \frac{\partial \mathbf{I}(\lambda)}{\partial X[\tau_c]}$$

This is a two-dimensional function that tells us how a Stokes parameters changes as a function of wavelength, λ, when a physical parameter is perturbed in the optical depth τ_c. Example:

$$\mathcal{R}_{\mathrm{I},\mathrm{T}}(\lambda, \tau_c) = \frac{\partial I(\lambda)}{\partial T[\tau_c]} \; ; \; \mathcal{R}_{\mathrm{V},\mathrm{B}}(\lambda, \tau_c) = \frac{\partial V(\lambda)}{\partial B[\tau_c]}$$

Response functions were first introduced by Landi Degl'Innocenti & Landi Degl'Innocenti (1977)

$\mathcal{R}(\tau_c, \lambda)$ calculation using SIR

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Sep 02, 19 15:00 **sir.trol** Page 1/2

```
Number of cycles           (*):-1              ! (0=synthesis)
Observed profiles          (*):example1.per    !
Stray light file              :                ! (none=no stray light contam)
PSF file                      :                ! (none=no convolution with PSF)
Wavelength grid file       (s):example.grid    ! (none=automatic selection)
Atomic parameters file        :LINES_example   ! (none=DEFAULT LINES file)
Abundances file               :THEVENIN        ! (none=DEFAULT ABUNDANCES file)
Initial guess model 1      (*):example1.mod    !
Initial guess model 2         :
Weight for Stokes I           :0               ! (DEFAULT=1; 0=not inverted)
Weight for Stokes Q           :0               ! (DEFAULT=1; 0=not inverted)
Weight for Stokes U           :0               ! (DEFAULT=1; 0=not inverted)
Weight for Stokes V           :1               ! (DEFAULT=1; 0=not inverted)
AUTOMATIC SELECT. OF NODES?   :                ! (DEFAULT=0=no; 1=yes)
Nodes for temperature 1       :
Nodes for electr. press. 1    :
Nodes for microturb. 1        :
Nodes for magnetic field 1    :1
Nodes for LOS velocity 1      :
Nodes for gamma 1             :
Nodes for phi 1               :
Invert macroturbulence 1?     :                ! (0 or blank=no, 1=yes)
```

(a) Cycles: -1 (response function)

(b) Atmospheric model: *.mod $\Rightarrow$ must be equidistant in $\log \tau_5$ to calculate $\mathcal{R}$

(c) Set to 1 those Stokes parameteres for which you want $\mathcal{R}$

(d) Set to 1 those physical parameters for which you want $\mathcal{R}$

$\mathcal{R}(\tau_c, \lambda)$ calculation using SIR

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- Exercise: calculate reponse functions of Stokes V to magnetic field strength: $\mathcal{R}_{\mathrm{V,B}}(\lambda, \tau_c)$
- Run sir using the atmosphetric model example1.mod inside directory rf_examples/ with No. cycles $= -1$
- SIR will produce synthetic profiles example1.per plus files containing response function: example1.rh.
- use import sir_utils as su and use plot_rf_vb('dir','file.rh','file.mod')

$\mathcal{R}(\tau_c, \lambda)$ calculation using SIR

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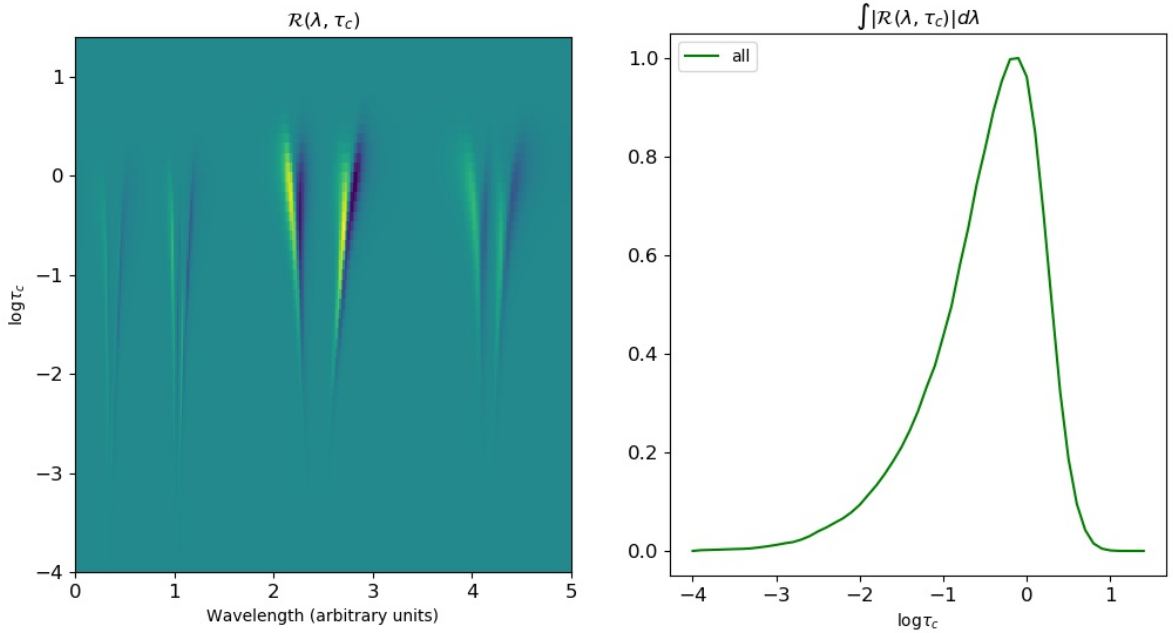

- With this you can calculate the optimal $\log\tau_5^\dagger$ to correlate $\mathcal{C}$ with $B_{||}$ and $\mathcal{L}$ with $B_\perp$

$\mathcal{R}(\tau_c, \lambda)$ calculation using SIR

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- Exercise: calculate reponse functions of Stokes *I* to temperature: $\mathcal{R}_{\mathrm{I,T}}(\lambda, \tau_c)$
- Run sir using the atmosphetric model example1.mod inside directory rf_examples/ with No. cycles $= -1$
- Do not forget to change sir.trol file.
- SIR will produce synthetic profiles example1.per plus files containing response function: example1.rt.
- use import sir_utils as su and use plot_rf_it('dir','file.rt','file.mod')

$\mathcal{R}(\tau_c, \lambda)$ calculation using SIR

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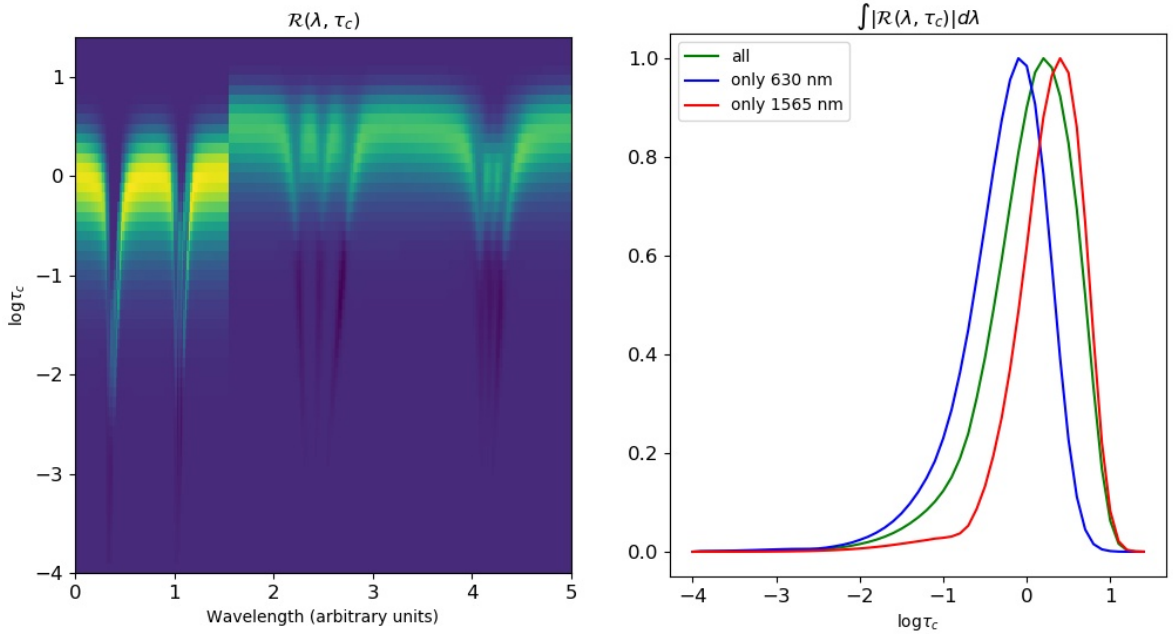

- With this you can calculate the optimal $\log\tau_5^\dagger$ to correlate $I_{c,630}$ and $I_{c,1565}$ with T
- Note that changing the temperature at $\log\tau_5 \approx 0$ changes the continuum intensity.
- Note that changing the temperature at $\log\tau_5 \approx -3$ changes the core intensity.
- We saw this in the Section 'Temperature effects'

Inversion of Stokes profiles in a nutshell

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$$\text{Synthesis} : \mathbf{X}[\tau_c] \implies \mathbf{I}^{\rm syn}(\lambda, \mathbf{X}[\tau_c])$$
$$\text{Inversion} : \mathbf{I}^{\rm obs}(\lambda) \implies \mathbf{X}[\tau_c]$$

The inversion is done by minimizing a merit-function χ^2 defined as:

$$\chi^2 \propto \sum_k^{N_\lambda} \sum_{j=1}^{4} w_j [I_j^{\rm obs}(\lambda_k) - I_j^{\rm syn}(\lambda_k, \mathbf{X}[\tau_c])]^2 \qquad (5)$$

A recent and extensive review on this topic can be found in del Toro Iniesta & Ruiz Cobo (2016). The inversion is carried out by calculating the derivatives of χ^2 with respect to the physical parameters $\mathbf{X} \Rightarrow$ response functions !!

Test: inversion of Stokes spectra

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- Enter directory: inversion_examples/
- We will invert Stokes profiles penumbra.per that were previously synthesized with the model penumbra.mod. Our initial atmospheric model is guess.mod
- Edit sir.trol as:

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Sep 03, 19 12:05 **sir.trol** Page 1/2

```
Number of cycles           (*):2                ! (0=synthesis)
Observed profiles          (*):penumbra.per     !
Stray light file              :                 ! (none=no stray light contam)
PSF file                      :                 ! (none=no convolution with PSF)
Wavelength grid file       (s):example.grid     ! (none=automatic selection)
Atomic parameters file        :LINES_example    ! (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           :1                 ! (DEFAULT=1; 0=not inverted)
Weight for Stokes U           :1                 ! (DEFAULT=1; 0=not inverted)
Weight for Stokes V           :1                 ! (DEFAULT=1; 0=not inverted)
AUTOMATIC SELECT. OF NODES?   :                  ! (DEFAULT=0=no; 1=yes)
Nodes for temperature 1       :2,3
Nodes for electr. press. 1    :
Nodes for microturb. 1        :
Nodes for magnetic field 1    :2,5
Nodes for LOS velocity 1      :2,5
Nodes for gamma 1             :2,5
Nodes for phi 1               :2,5
Invert macroturbulence 1?     :                  ! (0 or blank=no, 1=yes)
```

Control file for inversions: sir.trol

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Sep 03, 19 12:05 **sir.trol** Page 1/2

```
Number of cycles          (*):2              ! (0=synthesis)
Observed profiles         (*):penumbra.per   ! (none=no stray light contam)
Stray light file             :               ! (none=no convolution with PSF)
PSF file                     :               ! (none=no convolution with PSF)
Wavelength grid file      (s):example.grid   ! (none=automatic selection)
Atomic parameters file       :LINES_example  ! (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          :1               ! (DEFAULT=1; 0=not inverted)
Weight for Stokes U          :1               ! (DEFAULT=1; 0=not inverted)
Weight for Stokes V          :1               ! (DEFAULT=1; 0=not inverted)
AUTOMATIC SELECT. OF NODES?  :                ! (DEFAULT=0=no; 1=yes)
Nodes for temperature 1      :2,3
Nodes for electr. press. 1   :
Nodes for microturb. 1       :
Nodes for magnetic field 1   :2,5
Nodes for LOS velocity 1     :2,5
Nodes for gamma 1            :2,5
Nodes for phi 1              :2,5
Invert macroturbulence 1?    :                ! (0 or blank=no, 1=yes)
```

(a) Cycles: 2 (two inversion cycles)

(b) 'Observed' profiles we just copied $\Rightarrow$ we aim at fitting these.

(c) Inital guess atmospheric model.

(d) w_j in Eq(5). If 0 Stokes parameter is ignored and not fitted.

(e) Number of nodes for each inverted physical parameter: cycle #1, cycle #2

Test: inversion of Stokes spectra

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- Run SIR as always: echo sir.trol | ./sir.x
- Output best-fit profiles: name of the guess model +'_1,_2', etc. One file per inversion cycle. guess_1.per, guess_2.per
- Output atmospheres: name of the guess model +'_1,_2', etc. One file per inversion cycle. guess_1.mod, guess_2.mod
- Use: import sir_utils as su and su.plot_matm(dir,['file1.mod','file2.mod',...]) to plot resulting physical parameters.

Physical parameters: inversion of Stokes spectra

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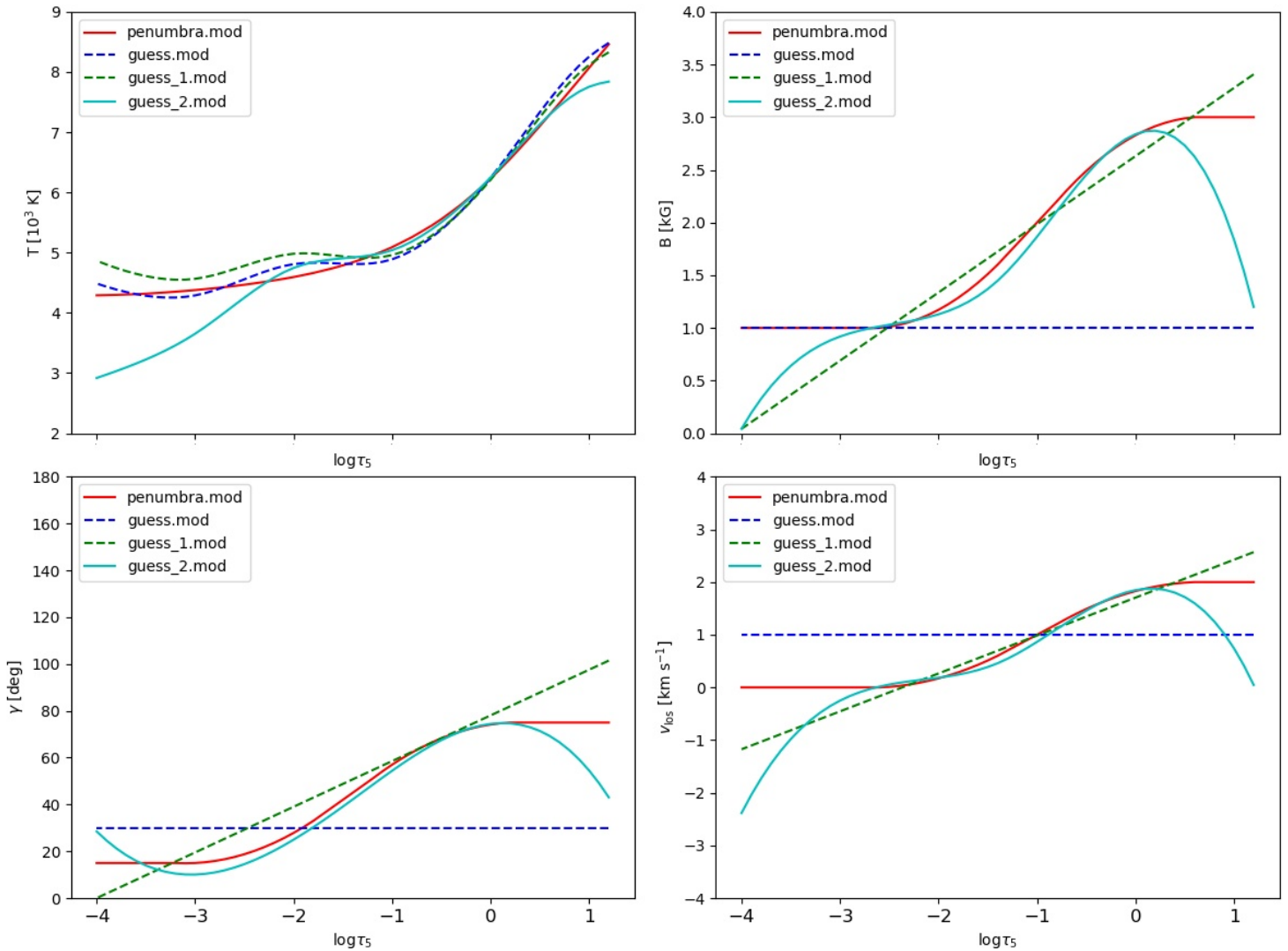

Fitted/observed Stokes profiles: inversion of Stokes spectra

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