Solar Spectropolarimetry

J. M. Borrero
fistro@leibniz-kis.de

Institut für Sonnenphysik (KIS)
Stiftung des öffentlichen Rechts des Landes Baden-Württemberg

Freiburg im Breisgau

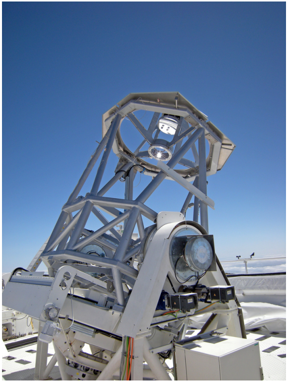
June 29, 2025

Outline

- Quick and simple overview on:
  - Spectropolarimetric observations
  - Spectropolarimetry and Stokes inversions
  - Formation of spectral lines: $\lambda \rightarrow \tau, z$ mapping
  - Polarization in spectral lines: the polarized radiative transfer equation
- Synergy between spectropolarimetry and MHD: past, present, and future
- Synergy between spectropolarimetry and atomic physics
- Conclusions

Spectropolarimetric observations

GREGOR telescope



GRIS instrument

- Alt-azimuthal mount with 1.5 meters concave primary mirror (cooled) and 0.42 meters concave secondary.
- Two focal points between M1 & M2. F1: heat rejector (cooled). F2: polarimetric calibration unit.
- Image derotator and AO system (DM with 256 actuators and 156 sub-apertures).

- Spectrograph and FLC modulators
- Signal to noise: $10^3 - 5 \times 10^4$
- Provides: $\mathbf{S}(x[t], y, \lambda)$, where $\mathbf{I} = (I, Q, U, V)$
- talk by Manolo Collados (IAC; Tenerife) on Wednesday

The radiative transfer equation (RTE) for polarized light

$$\frac{\mathrm{d}}{\mathrm{d}z}\begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix} = -\begin{pmatrix} \eta_i & \eta_q & \eta_u & \eta_v \\ \eta_q & \eta_i & \rho_v & -\rho_u \\ \eta_u & -\rho_v & \eta_i & \rho_q \\ \eta_v & \rho_u & -\rho_q & \eta_v \end{pmatrix}\begin{pmatrix} I - S \\ Q \\ U \\ V \end{pmatrix}$$

$$\frac{\mathrm{d}\mathbf{I}}{\mathrm{d}z} = -\hat{K}[\mathbf{I} - \mathbf{S}]$$

- Coupled system of 4 first-order ODE
- η, ρ: depend on the medium properties: T, $\mathbf{B}$, v_z and also important:
- S depends on T (LTE) but also on $\mathbf{B}$, v_z, and $\int I \mathrm{d}\Omega$ (NLTE)

Why polarized light ? where does it come from ?

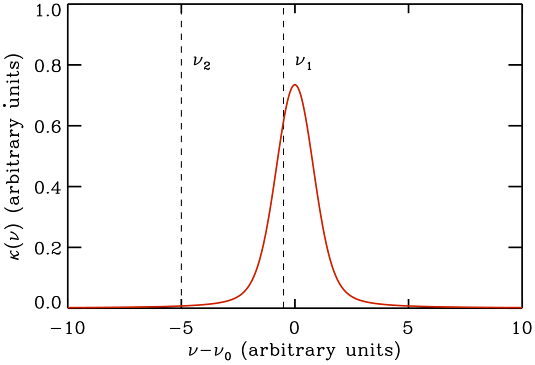
- Polarization appears because there is a phase lag δ between E_x and E_y components of the electric field $\mathbf{E}$
- The phase lag δ arises from having different phase speeds v_{ph} along x and y $\rightarrow$ anisotropy
- What produces the anisotropy ? The solar magnetic field $\mathbf{B}$
- How ? Because of the Lorentz force: $\mathbf{F}_{\mathrm{lor}} \perp \mathbf{B}$ $\rightarrow$ the dieletric constant and conductivity become matrices: $\mathbf{D} = \hat{\varepsilon}\mathbf{E}$, $\mathbf{j} = \hat{\sigma}\mathbf{E}$.
- In the RTE $\hat{K}$: $\eta(\sigma)$ and $\rho(\varepsilon)$

Spectropolarimetry and Stokes inversion in a nutshell

$$[T(x,y,z), v_z(x,y,z), \mathbf{B}(x,y,z)] \;\; \underset{\text{inverse}}{\overset{\text{forward}}{\rightleftarrows}} \;\; \mathbf{I}(x,y,\lambda)$$

$\lambda/\nu \to z$ mapping

Typical (i.e. Voigt) absorption probability $\kappa_{\mathrm{bb}}(\nu)$ for a bound-bound electronic energy level



- $\kappa_{\mathrm{bb}}(\nu_1)\upuparrows$; photon mean-free-path $\downdownarrows$; distance from us $\downdownarrows$; depth into the Sun $\downdownarrows$
- $\kappa_{\mathrm{bb}}(\nu_2)\downdownarrows$; photon mean-free-path $\upuparrows$; distance from us $\upuparrows$; depth into the Sun $\upuparrows$
- As we scan in λ, ν, we are in fact sampling different z's

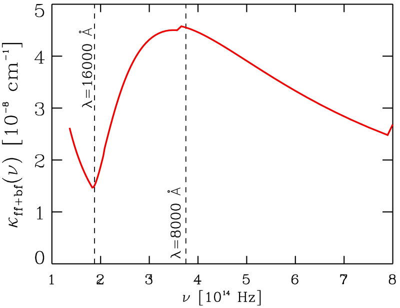
How deep are we talking about ?

$$z_{\max} \approx \frac{1}{\kappa_{\min}} = \frac{1}{\cancelto{0}{\kappa_{\rm bb}} + \kappa_{\rm bf} + \kappa_{\rm ff}}$$

$z_{\max} \approx 550$ km !!!

- We barely scratch the surface !
- To go deeper: use helioseismology
- or use neutrinos ! $\kappa_{\min} \to 0$; $z_{\max} \to \infty$

$\kappa_{\rm bb}$ and $\kappa_{\rm bf}$ due to H^-



- Chandrasekhar & Breen 1946

Synergy between spectropolarimetry and MHD

Stokes inversion

$$\frac{\mathrm{d}\mathbf{I}}{\mathrm{d}z} = -\hat{K}[\mathbf{I} - \mathbf{S}]$$

$+$ EOS
$+$ Saha $+$ Boltzmann (LTE)
$+$ SSE (NLTE)

$$\Downarrow$$

$T(\mathbf{r},t)$, $v_z(\mathbf{r},t)$, $\mathbf{B}(\mathbf{r},t)$

$$\Leftrightarrow$$

MHD simulations

$$\frac{\mathrm{D}\rho}{\mathrm{D}t} + \rho\nabla\cdot\mathbf{v} = 0$$

$$\rho\frac{\mathrm{D}\mathbf{v}}{\mathrm{D}t} = -\nabla P_{\mathrm{g}} + \rho\mathbf{g} + \nabla\cdot\hat{\tau} + \frac{1}{4\pi}(\nabla\times\mathbf{B})\times\mathbf{B}$$

$$\frac{\mathrm{D}\ln T}{\mathrm{D}t} + (\Gamma_3 - 1)\nabla\cdot\mathbf{v} = \frac{\mathscr{L}}{\rho c_v T}$$

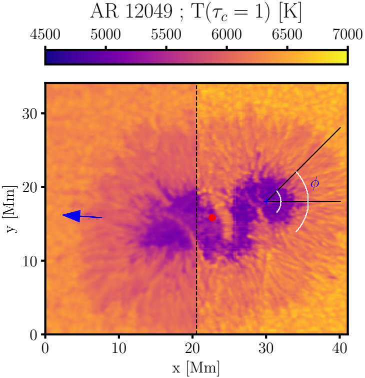
$$\frac{\partial\mathbf{B}}{\partial t} = \nabla\times(\mathbf{v}\times\mathbf{B}) + \eta_{\mathrm{diff}}\nabla^2\mathbf{B}$$

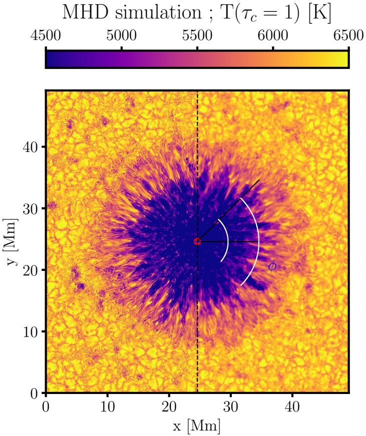
$+$ boundary cond $+$ ini cond $+$ EOS

$$\Downarrow$$

$T(\mathbf{r},t)$, $\mathbf{v}(\mathbf{r},t)$, $\mathbf{B}(\mathbf{r},t)$, $P_{\mathrm{g}}(\mathbf{r},t)$, $\rho(\mathbf{r},t)$

Comparing results from Stokes inversions and MHD simulations





- Comparison cannot be done is a point by point basis
- Comparison must be done statistically: correlations, histograms, power-spectrum, etc.
- Some quantities cannot be compared: P_g, ρ, v_x, v_y

A 25 years-old prediction ...

contain the essential physical ingredients to understand that particular problem. The physical scenario assumed in the inversion will become more realistic by introducing more MHD constraints.

On a somewhat longer term, we may witness the development of "dynamic" ICs, where the time evolution of the model is taken into account. Instead of analyzing the individual profiles in a time-series independently of each other, as it is presently done (see, e.g., Rodríguez Hidalgo et al., in this volume), a fully consistent treatment of the problem will proceed in the following manner: for the current guess model and boundary conditions, the time-evolution of the atmosphere is calculated by means of a numerical MHD simulation. The emergent profiles are then synthesized for each time in the simulation. Finally, the synthetic profiles (after averaging to account for the finite integration time in the observations) are compared with the observed time-series, and the model is modified so that the new numerical simulation will produce profiles that are more similar to the observed ones. For this scheme to work, it is obviously necessary that the MHD simulation be based on a realistic scenario. Otherwise, it is very unlikely that the whole observed time-series could be consistently fitted. Since modern instrumentation provides us with time-series of Stokes profiles over a whole 2D region, this kind of inversions is, in my opinion, the best tool to exploit the current observations. In particular, it is the only way to consistently account for the finite integration time and also for the time lag between the different slit positions in a given scan.

The scheme described above somehow represents a merging between ICs and MHD simulation codes, and may sound like something new. But, in fact, this merging process has been already taking place during the last years. As discussed in this paper, the most recent ICs are already making use of MHD constraints (although they still consider time-independent models), while the

Stokes inversions + MHD: (1) the past

Stokes inversion

$\Downarrow$

$T(\mathbf{r}, t)$, $v_z(\mathbf{r}, t)$, $\mathbf{B}(\mathbf{r}, t)$

$\Downarrow$

momentum equation: 1D hydrostatic equilibrium

$$\frac{\partial P_{\mathrm{g}}}{\partial z} = -\frac{m_{\mathrm{a}} g}{K} \frac{\mu(T)}{T} P_{\mathrm{g}}$$

$\Downarrow$

$P_{\mathrm{g}}(z, t)$, $\rho(z, t)$

Not very accurate and only dependent on z 😩

Stokes inversions + MHD: (2) the present

Stokes inversion

$\Downarrow$

$T(\mathbf{r},t)$, $v_z(\mathbf{r},t)$, $\mathbf{B}(\mathbf{r},t)$

$\Downarrow$

momentum equation: 3D magneto-hydrostatic equilibrium

$$\nabla P_{\rm g} = -\frac{m_{\rm a}\mathbf{g}}{K}\frac{\mu(T)}{T}P_{\rm g} + \frac{1}{4\pi}(\nabla\times\mathbf{B})\times\mathbf{B}$$

$\Downarrow$

$P_{\rm g}(\mathbf{r},t)$, $\rho(\mathbf{r},t)$

Much more accurate in active regions (i.e. sunspots) and full **r** dependence 😄

Stokes inversions + MHD: (3) the near future

Stokes inversion

$\Downarrow$

$T(\mathbf{r},t)$, $v_z(\mathbf{r},t)$, $\mathbf{B}(\mathbf{r},t)$

$\Downarrow$

momentum: 3D magneto-hydrostationary equilibrium

$$\nabla P_{\rm g} = -\frac{m_{\rm a}}{K}\frac{\mu(T)}{T}[\mathbf{g}-(\mathbf{v}\cdot\nabla)\mathbf{v}]P_{\rm g} + \frac{1}{4\pi}(\nabla\times\mathbf{B})\times\mathbf{B}$$

But we only know $v_z(\mathbf{r},t)$ and we need $\mathbf{v}(\mathbf{r},t)$ $\rightarrow$ induction equation

$$\frac{\partial\mathbf{B}}{\partial t} = \nabla\times(\mathbf{v}\times\mathbf{B})$$

Over-determined system: 3 equations, 2 unknowns (v_x, v_y)

$\Downarrow$

$P_{\rm g}(\mathbf{r},t)$, $\rho(\mathbf{r},t)$, $v_x(\mathbf{r},t)$, $v_y(\mathbf{r},t)$

Much more accurate in regions with large velocities (i.e. chromosphere) 🤞

see poster by Helena Vila Crespo

Stokes inversions + MHD constraints: (4) the future

Stokes inversion + momentum equation + induction equation

$\Downarrow$

$T(\mathbf{r},t)$, $\mathbf{v}(\mathbf{r},t)$, $\mathbf{B}(\mathbf{r},t)$, $P_{\rm g}(\mathbf{r},t)$, $\rho(\mathbf{r},t)$

$\Downarrow$

$$\frac{\mathrm{D}\ln T}{\mathrm{D}t} + (\Gamma_3 - 1)\nabla\cdot\mathbf{v} = \frac{\mathscr{L}}{\rho c_v T}$$

$\Downarrow$

$$\mathscr{L}(\mathbf{r},t) = \mathscr{L}_{\rm rad} + \mathscr{L}_{joule} + \mathscr{L}_{\rm visc} + \ldots$$

First empirical determination of the total loss term (can we isolate individual contributions ?)

Stokes inversions + MHD constraints: (5) the future

Stokes inversion

$\Downarrow$

$T(\mathbf{r},t)$, $v_z(\mathbf{r},t)$, $\mathbf{B}(\mathbf{r},t)$

$\Downarrow$

magneto-hydrostationary + isoentropic process + anelastic

$$\nabla\left(\frac{P_\mathrm{g}}{T}\mathbf{v}\right)=0$$

$$\nabla P_\mathrm{g}=-\frac{m_\mathrm{a}}{K}\frac{\mu(T)}{T}[\mathbf{g}-(\mathbf{v}\cdot\nabla)\mathbf{v}]P_\mathrm{g}+\frac{1}{4\pi}(\nabla\times\mathbf{B})\times\mathbf{B}$$

$$\frac{\mathrm{D}\ln T}{\mathrm{D}t}+(\Gamma_3-1)\nabla\cdot\mathbf{v}=0$$

$$\frac{\partial\mathbf{B}}{\partial t}=\nabla\times(\mathbf{v}\times\mathbf{B})$$

$\Downarrow$

Highly over-determined system: 8 equations, 3 unknowns (P_g, v_x, v_y)

Stokes inversions + MHD: inversion uncertainty

- Stokes inversion **does not** retrieve T, v_z, $\mathbf{B}$ with infinite accuracy: ΔT, Δv_z, $\Delta \mathbf{B}$ (errors/uncertainties)
- Is using these physical parameters as the input of the MHD equations to infer $P_{\rm g}$, v_x, v_y, $\mathscr{L}$, etc. safe or just a flagrant case of GI-GO ?
- The use of over-determined systems should help, but it implies slightly less realistic physical approximations (i.e. iso-entropic evolution): use full 3D MHD simulations to benchmark the method: $\Rightarrow$ see Helena Vila Crespo's poster for further results/ideas.
- Expanding the known (T, v_z, $\mathbf{B}$) and unknown ($P_{\rm g}$, v_x, v_y,...) into basis functions would produce further over-determined systems and yield smooth solutions $\Rightarrow$ see Andreu Vicente Arévalo's poster for further results/ideas.

The Sun as a laboratory for atomic physics

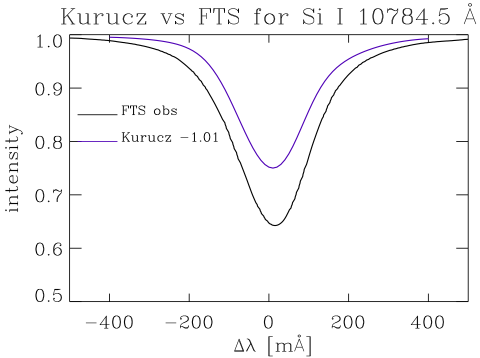
- The η and ρ elements of the $\hat{K}$ matrix in radiative transfer equation are calculated by considering the theory of light-matter interaction (i.e. QM)
- In many cases, the QM constants needed are only approximately known: oscillator strengths, partition functions, collisional cross-sections, etc.
- This negatively affects our ability to infer T, P_{g}, **B**, abundances, etc.

Oscillator strengths (1)

- line (bb) absorption coefficient:

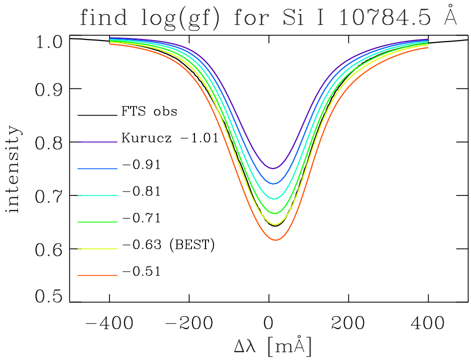
$$\kappa_{\mathrm{bb}} \propto gf$$

- NIST database: scarce data but high quality (lab measurements)
  - Stockholm (Edlen & Risberg et al.): 1950's - 1960's
  - Oxford (Blackwell et al.): mid 1980's-mid 1990's
  - Hannover/Kiel (Bard & Kock et al.): early 1990's
- VALD and Kurucz databases: exhaustive but inaccurate (theoretical/numerical)



Oscillator strengths (2)

- If you have a trustworthy models for the solar atmosphere: $T(z)$, $v_z(z)$, $P_g(z)$ you can use it to determine *gf*: Gurtovenko et al. (early 80's), Thévenin (early 90's), Borrero & Bellot Rubio (early 2000's)
- Determination of element abundances need accurate *gf* values !



Oscillator strengths (3)

- NIST considers solar gf's of low quality: 😭
- Dusan Vukadinovic new method seems very promising but needs to be applied to actual data (Sunrise ?)

Kramida, A., Ralchenko, Yu., Reader, J., and NIST A
Atomic Spectra Database (ver. 5.12), [Online]. Availa
physics.nist.gov/asd [2025, June 28]. National Institu
Technology, Gaithersburg, MD. DOI: https://doi.org/1
B

Ti I: 4 Lines of Data Found
Z = 22, Ti isoelectronic sequence

Wavelength range: 1070 - 1074 nm
λ in: vacuum below 200 nm, air between 200 and 2000 nm, vacuum above 2000 nm
Highest relative intensity: 1200
Some data for neutral and singly-charged ions are available in the Handbook of Basic Atomic Spectroscopic Data

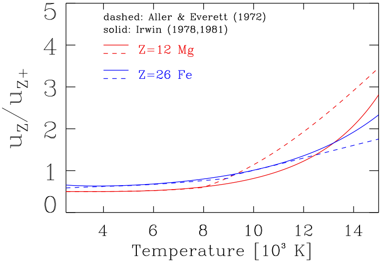
	Primary data sources	Query NIST Bibliographic Databases for Ti I (new window)
Energy Levels:	Saloman 2012	Ti I Energy Levels
Lines:	Saloman 2012	Ti I Line Wavelengths and Classification
Transition Probabilities:	Martin et al. 1988, Morton 2003, Nitz et al. 1998, Borrero et al. 2003, Blackwell-Whitehead et al. 2006	Ti I Transition Probabilities

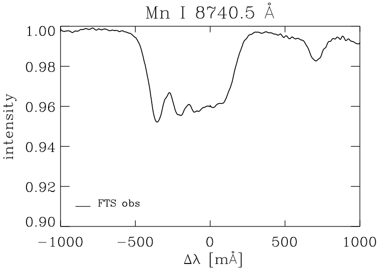
Observed Wavelength Air (nm)	Unc. (nm)	Ritz Wavelength Air (nm)	Unc. (nm)	Rel. Int. (?)	A_{ki} (s^{-1})	$\log(g_i f_{ik})$	Acc.	E_i (cm^{-1})		E_k (cm^{-1})	Lower Level Conf., Term, J			Upper Level Conf., Term, J		
1 072.6392	0.0014	1 072.6390	0.0005	1200				6 556.833	-	15 877.081	$3d^3(^4F)4s$	a ^5F	1	$3d^2(^3F)4s4p(^3P°)$	z $^5G°$	2
1 073.0934	0.0014	1 073.0927	0.0006	58				29 986.199	-	39 302.506	$3d^3(^4F)4p$	x $^5D°$	3	$3d^3(^4F)5s$	f ^5F	4
1 073.2868	0.0014	1 073.2865	0.0005	350	1.1e+04	-2.87	E	6 661.006	-	15 975.631	$3d^3(^4F)4s$	a ^5F	3	$3d^2(^3F)4s4p(^3P°)$	z $^5G°$	3
1 073.9817	0.0014	1 073.9801	0.0006	3				33 700.884	-	43 009.4937	$3d^3(^4F)4p$	w $^3F°$	4	$3d^4$	$^3F1$	4

If you did not find the data you need, please inform the ASD Team

Some additional aspects

- The most important contributor to the continuum (bf+ff) opacity is H^-. Its density is proportional to the electron density: $\kappa_{\mathrm{ff}} + \kappa_{\mathrm{bf}} \propto n_{H^-} \propto n_e$. The determination of n_e depends on the atoms partition functions through Saha's equation: $n_e \propto \frac{u_{Z^+}(T)}{u_Z(T)}$. Our knowledge of partition functions is rather limited.
- Some atomic species (i.e. Mn I) show clear signatures of hyperfine structure $\rightarrow$ very useful to study the solar surface magnetic field (López Ariste et al. 2002) $\rightarrow$ lack of good hyperfine structure constants. Sunrise's SUSI instrument has recorded spectra potentially very interesting for this.
- In Non-LTE calculations, collisions produce depolarization $\rightarrow$ the absorption/emission rates due to collisions are very inaccurate $\rightarrow$ work being done by Derouich & Barklem.





Conclusions

1. Solar spectropolarimetry is based on the radiative transfer equation.

Conclusions

1. Solar spectropolarimetry is based on the radiative transfer equation.
2. It describes the formation of spectral lines and their polarized spectra.

Conclusions

1. Solar spectropolarimetry is based on the radiative transfer equation.
2. It describes the formation of spectral lines and their polarized spectra.
3. It needs excellent atomic data: oscillator strengths, partition functions, collisional rates, etc.

Conclusions

1. Solar spectropolarimetry is based on the radiative transfer equation.
2. It describes the formation of spectral lines and their polarized spectra.
3. It needs excellent atomic data: oscillator strengths, partition functions, collisional rates, etc.
4. It allows us to infer the physical conditions (T, $\mathbf{B}$, v_z) on the solar atmosphere in a layer about 1-2 Mm thick.

Conclusions

1. Solar spectropolarimetry is based on the radiative transfer equation.
2. It describes the formation of spectral lines and their polarized spectra.
3. It needs excellent atomic data: oscillator strengths, partition functions, collisional rates, etc.
4. It allows us to infer the physical conditions (T, $\mathbf{B}$, v_z) on the solar atmosphere in a layer about 1-2 Mm thick.
5. Its inferences can be improved and supplemented (ρ, v_x, v_y, ...) by combining it with the MHD equations.

Conclusions

1. Solar spectropolarimetry is based on the radiative transfer equation.
2. It describes the formation of spectral lines and their polarized spectra.
3. It needs excellent atomic data: oscillator strengths, partition functions, collisional rates, etc.
4. It allows us to infer the physical conditions (T, $\mathbf{B}$, v_z) on the solar atmosphere in a layer about 1-2 Mm thick.
5. Its inferences can be improved and supplemented (ρ, v_x, v_y, ...) by combining it with the MHD equations.
6. If you trust these inferences we can use them to employ the Sun as a laboratory for atomic physics and help in the determination of atomic parameters.