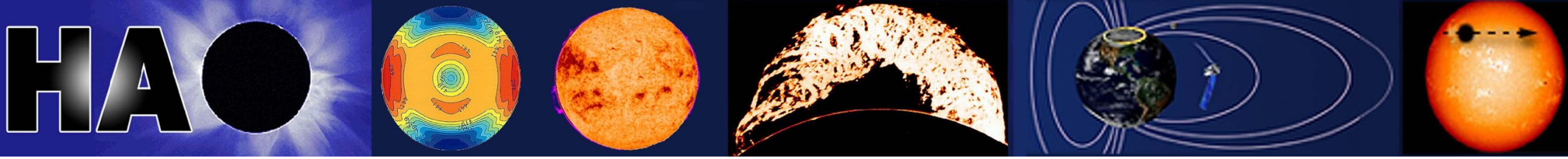


Experimental Testing of Scattering Polarization Models

R. Casini
W. Li, S. Tomczyk

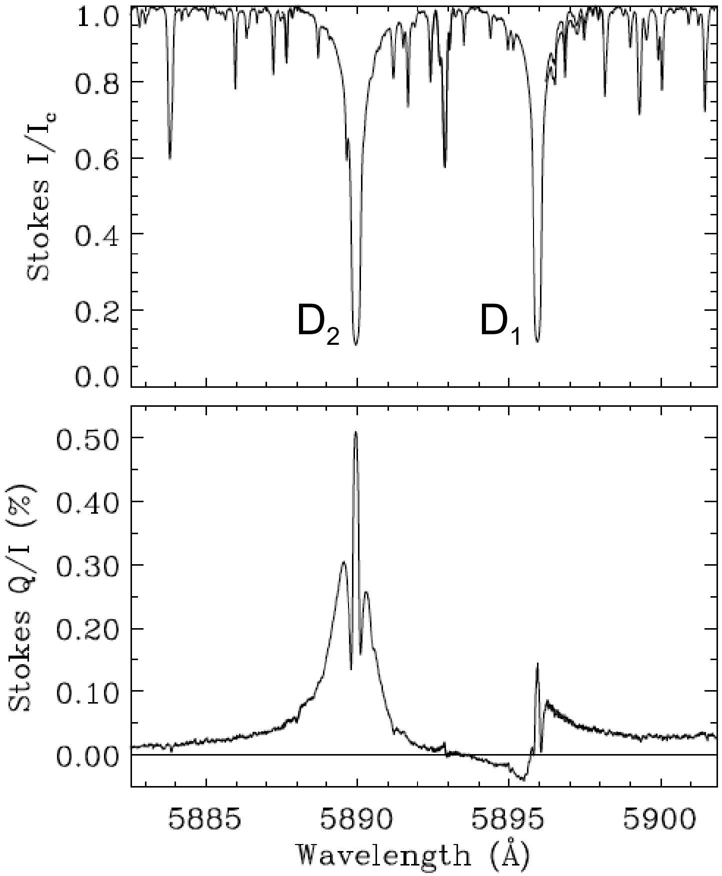
High Altitude Observatory
National Center for Atmospheric Research

Motivations

- Scattering polarization is a fundamental diagnostics of the magnetism of the upper solar atmosphere (e.g., Second Solar Spectrum [SS2], prominences, coronal line emission)
- Subtle quantum-mechanical effects (atomic polarization, Hanle effect, quantum interference, level-crossing physics,...) prevent a quantitative description of scattering polarization in terms of classical electrodynamics
- Theory has been applied with confidence to various observations (prominences, coronal line emission), but...
  - "enigmatic" polarization of Na I D_1: $J = 1/2 \rightarrow J' = 1/2$ (Stenflo & Keller 1996)
  - many other challenging signatures in the SS2

“Enigmatic” Solar Spectrum of Na I

Stenflo & Keller, Nature, **382**, 588 (1996)



D$_1$ λ589.6 nm: $\int (Q/I)\,\mathrm{d}\lambda \neq 0$
(after continuum subtraction)

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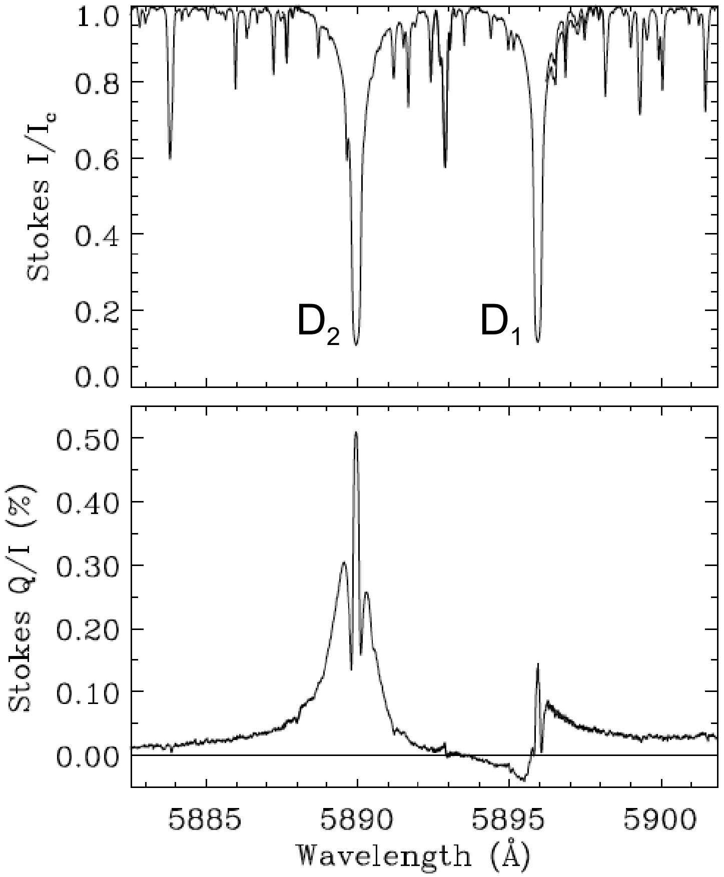
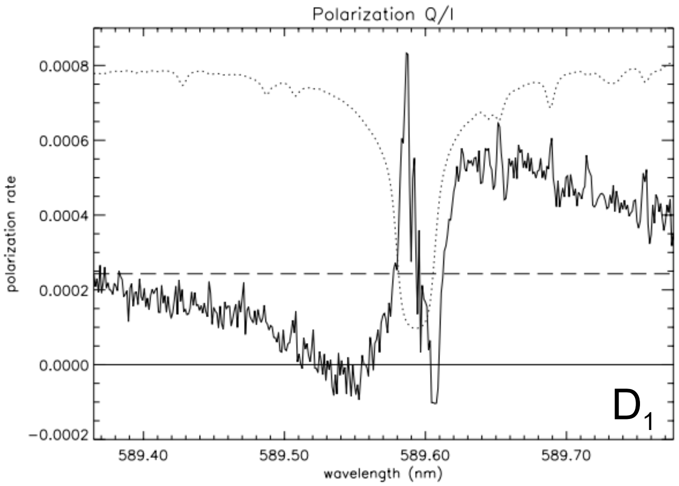


Bommier & Molodij, A&A, **381**, 241 (2002)



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(after continuum subtraction)

Must test the adequacy of the current quantum-electrodynamic theory of polarized line formation (Landi Degl’Innocenti & Landolfi 2004)

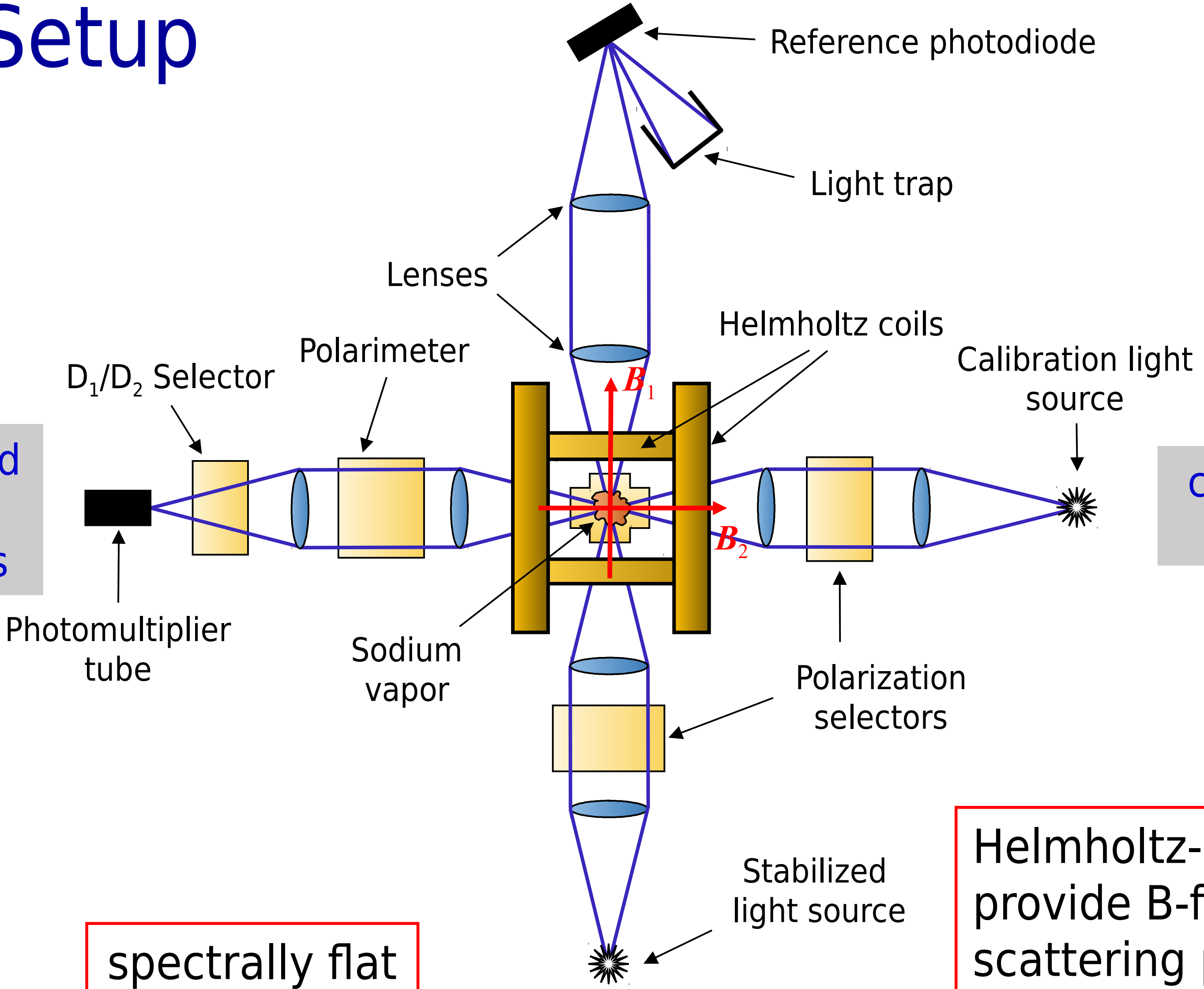
We designed a laboratory experiment with controlled conditions of magnetic field and scattering geometry

Experimental Setup

light-level monitoring

scattered light analysis

calibration channel



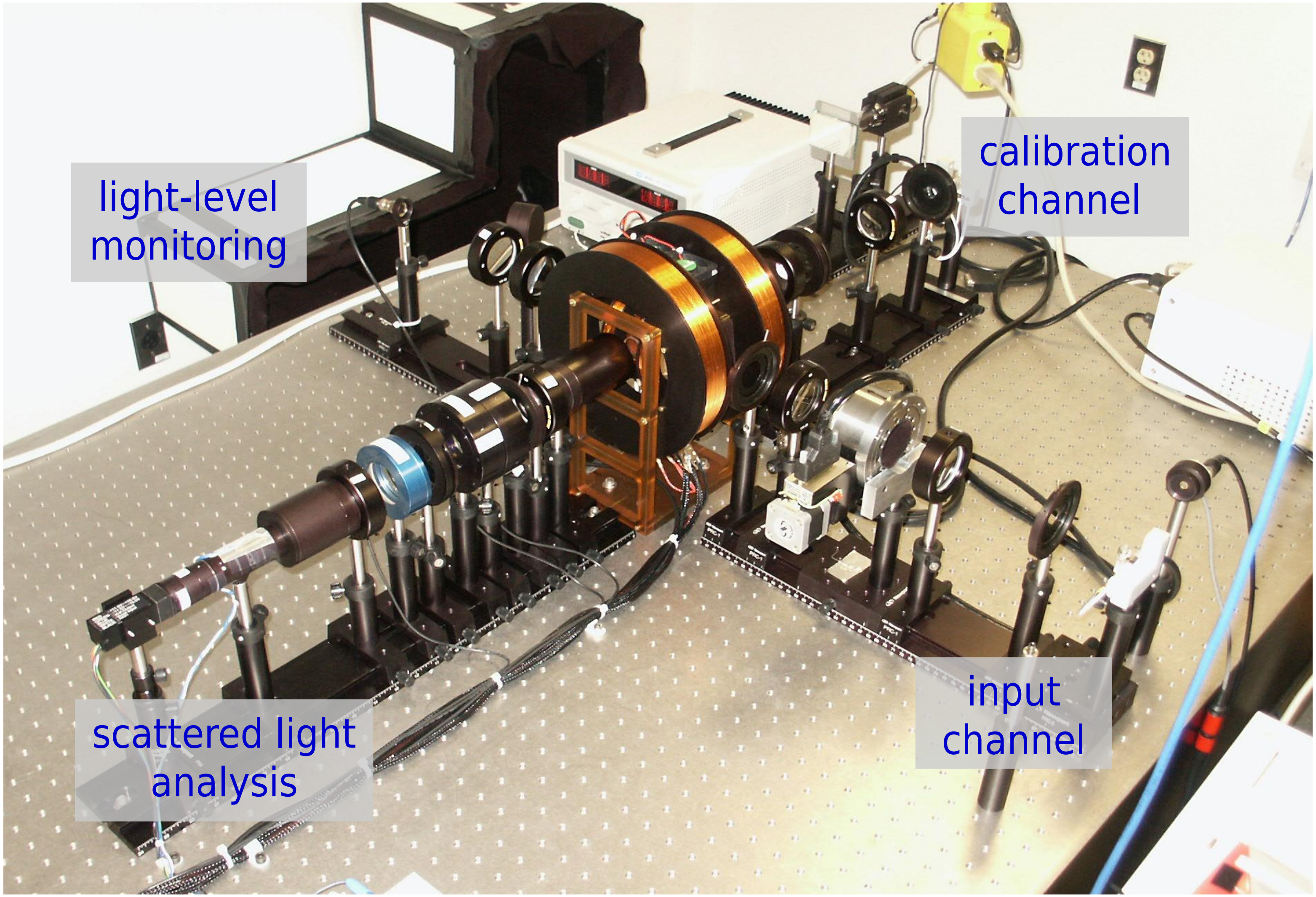
input channel

spectrally flat radiation

Helmholtz-coil pairs provide B-field in the scattering plane up to 150 G

Laboratory Scattering Experiment

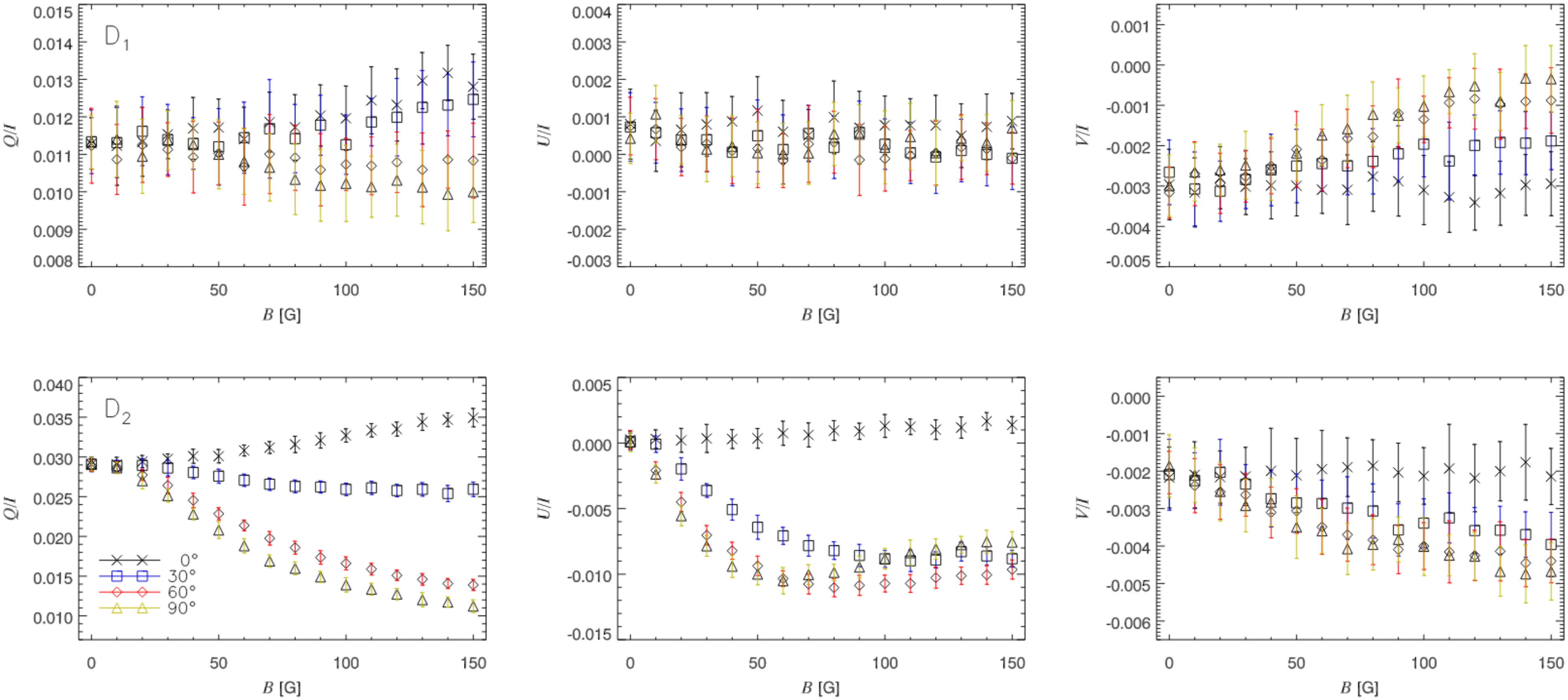
(NCAR Opportunity Funds 2004)



Experimental Results

(unpolarized input)

averaged over 12 different realizations of the experiment



Modeling Hypotheses

(1) Flat-spectrum illumination

- Complete Redistribution of radiation frequency (CRD)
- radiation scattering as incoherent succession of one-photon absorption and re-emission

(2) Elastic collisions (mainly with Ar buffer gas)

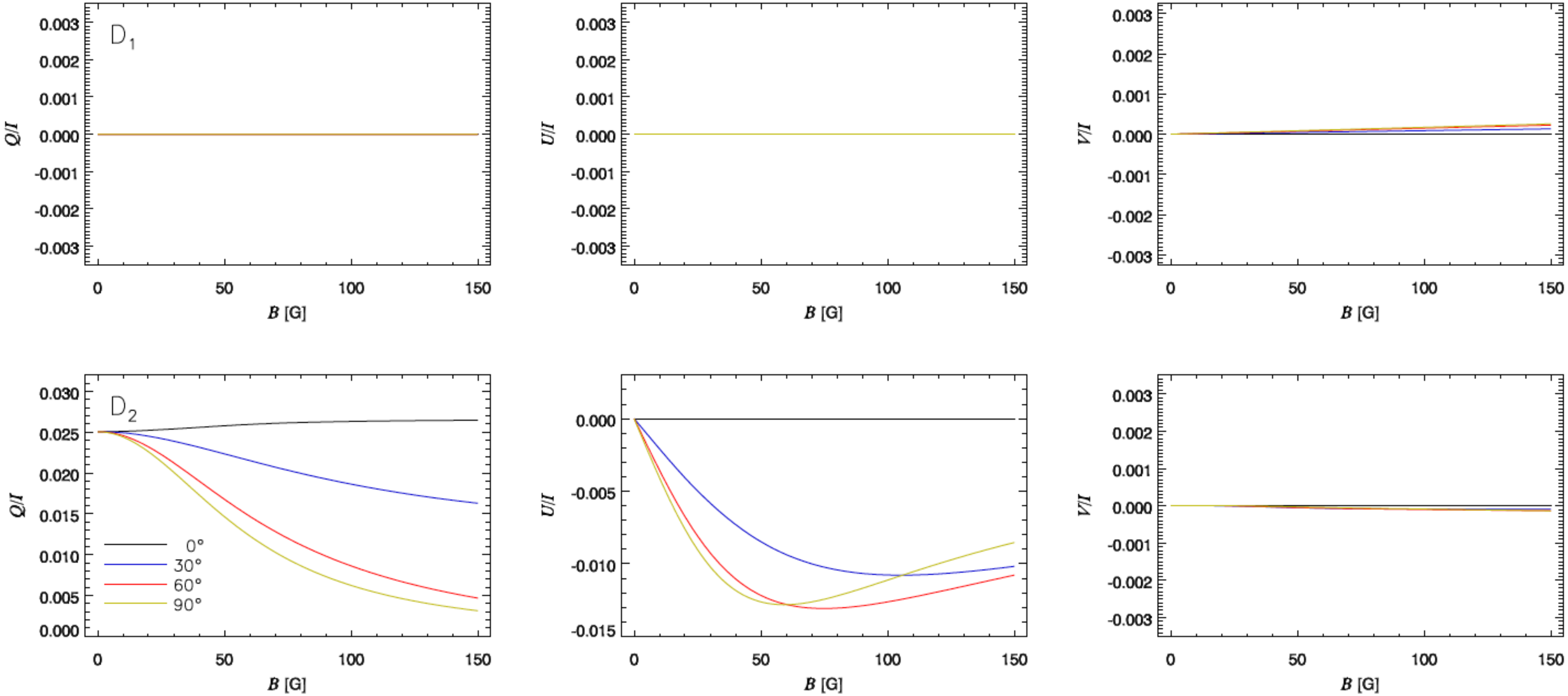
- depolarization of atomic levels with rates $\delta^{(1,2)}$ (orientation and alignment)
- ground level completely unpolarized (due to much longer lifetime)

(3) Optically thin vapor

Modeling Results for Na I

D_1 and D_2 emissivity

(unpolarized input, collisions)



Modeling Results for Na I

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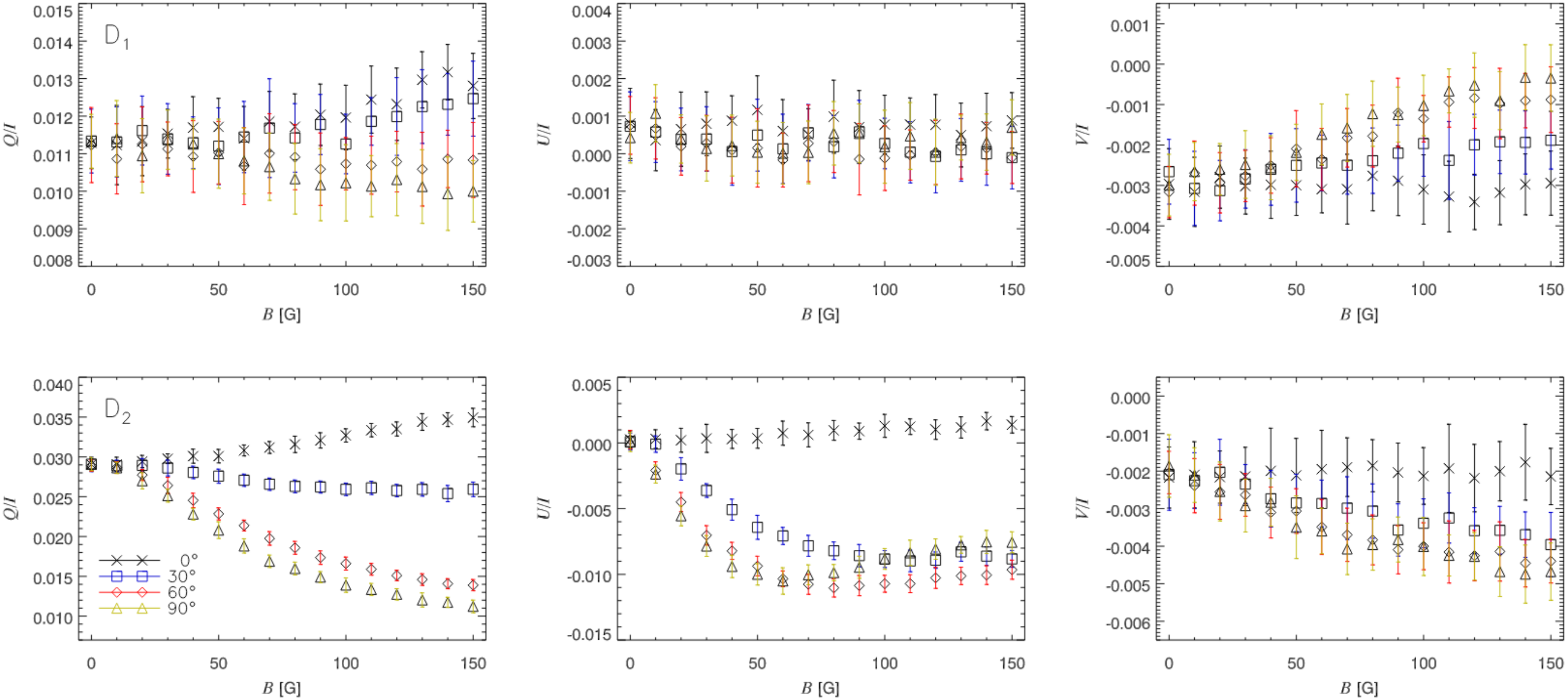

Additional Modeling Hypotheses

(3') Optically thick vapor

- differential saturation of line components
- magnetic-induced dichroism

(4) Inelastic collisions (Na-Na, cell walls)

- de-excitation of atomic levels with rate ϵ
- negligible excitation (cold vapor)

(5) Background radiation

- boundary term of the solution of the radiative transfer equation

Polarized Radiative Transfer

We solve numerically the radiative transfer equation for the polarized radiation of Stokes vector $\boldsymbol{S} = (I, Q, U, V)^T$

$$\frac{\mathrm{d}}{\mathrm{d}s}\boldsymbol{S} = -\mathbf{K}\,\boldsymbol{S} + \boldsymbol{\varepsilon}$$

$$\mathbf{K} \equiv \begin{pmatrix} \eta_I & \eta_Q & \eta_U & \eta_V \\ \eta_Q & \eta_I & \rho_V & -\rho_U \\ \eta_U & -\rho_V & \eta_I & \rho_Q \\ \eta_V & \rho_U & -\rho_Q & \eta_I \end{pmatrix}, \qquad \boldsymbol{\varepsilon} \equiv (\varepsilon_I, \varepsilon_Q, \varepsilon_U, \varepsilon_V)^T$$

for the multi-term atom with HFS (Casini & Manso Sainz 2005)

Polarized Radiative Transfer

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$$\frac{\mathrm{d}}{\mathrm{d}s}\boldsymbol{S} = -\mathbf{K}\,\boldsymbol{S} + \boldsymbol{\varepsilon}$$

dichroism

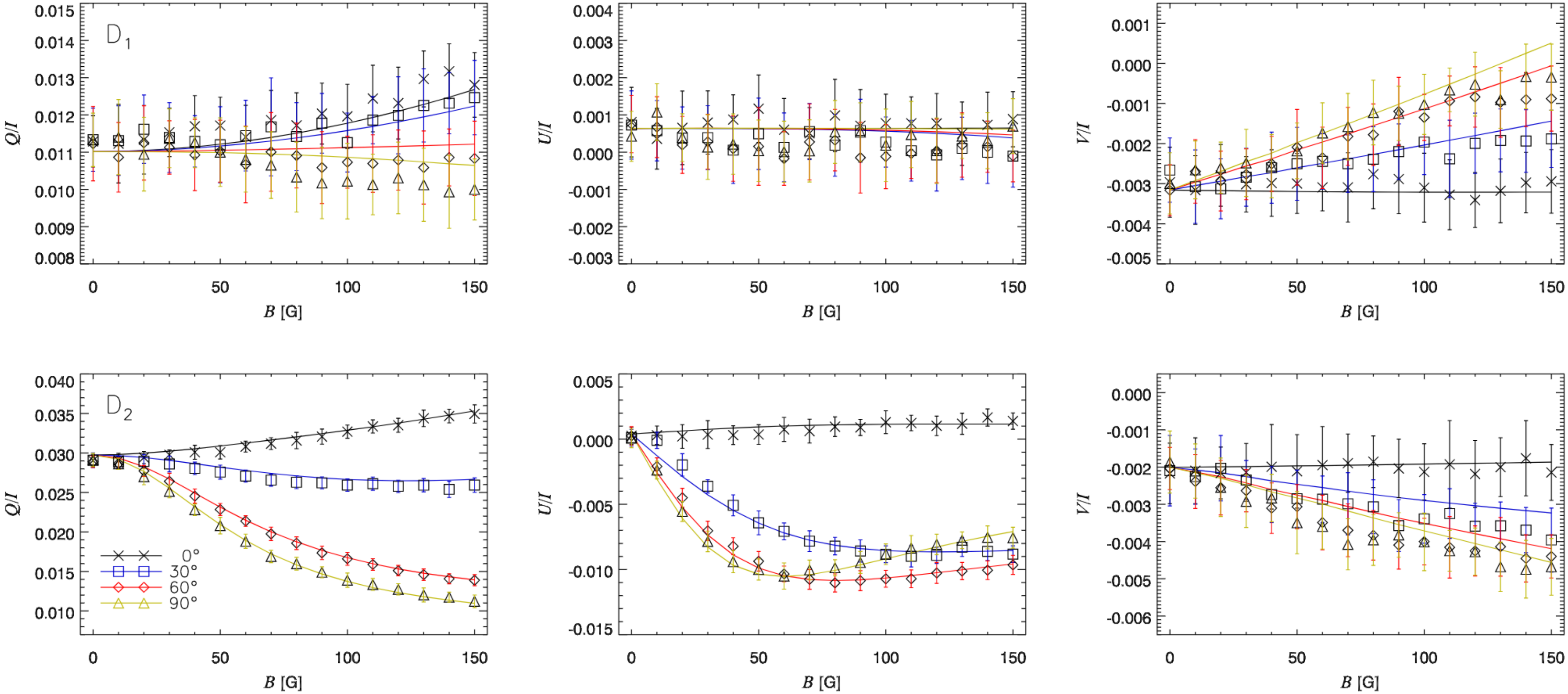
anomalous dispersion
(magneto-optical effects)

$$\mathbf{K} \equiv \begin{pmatrix} \eta_I & \eta_Q & \eta_U & \eta_V \\ \eta_Q & \eta_I & \rho_V & -\rho_U \\ \eta_U & -\rho_V & \eta_I & \rho_Q \\ \eta_V & \rho_U & -\rho_Q & \eta_I \end{pmatrix}, \qquad \boldsymbol{\varepsilon} \equiv (\varepsilon_I, \varepsilon_Q, \varepsilon_U, \varepsilon_V)^T$$

for the multi-term atom with HFS (Casini & Manso Sainz 2005)

Results

(optically thick vapor + background radiation)

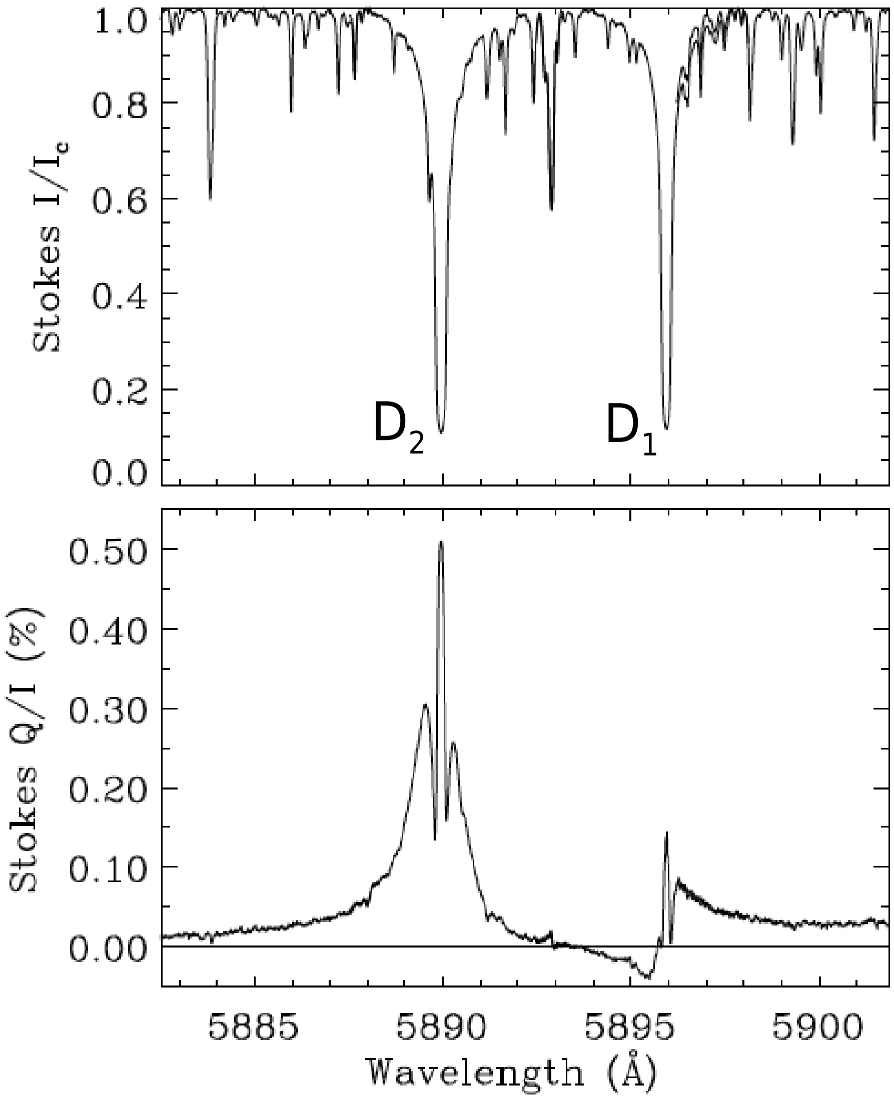


1. differential saturation effect ➔ V/I polarization ➔ $\tau_{D2} \approx 1.3$
2. Q/I and U/I of D$_2$ ➔ $\delta^{(2)} \approx 19$
3. zero-field value of Q/I polarization of D$_2$ ➔ $\epsilon \approx 0.44$

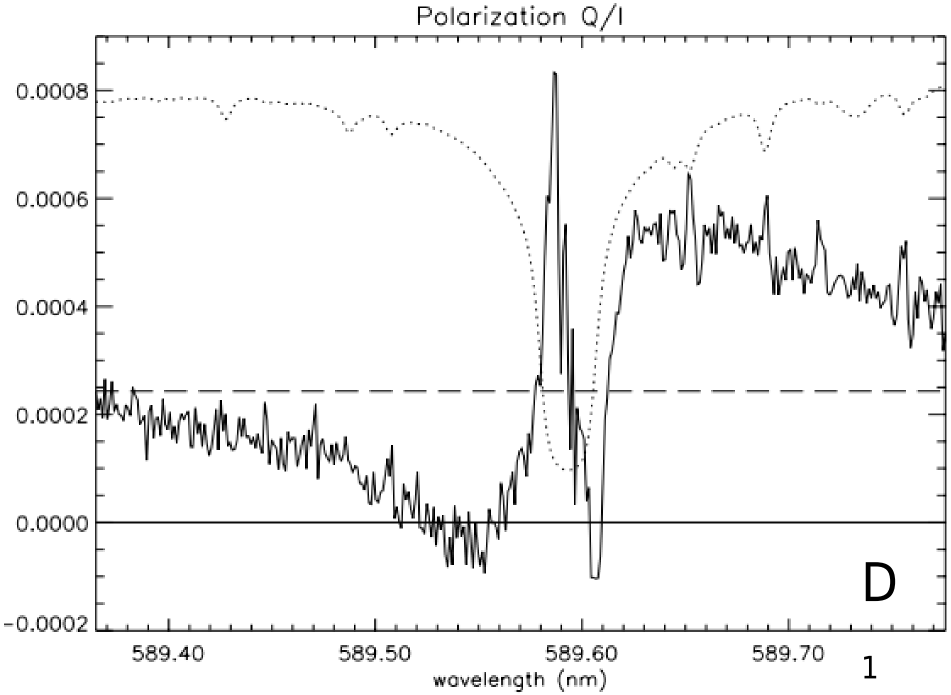
Model agreement confirms that the current QED theory of scattering polarization in the CRD limit (Landi Degl'Innocenti & Landolfi 2004) is correct, when the incident radiation is spectrally flat across the atomic transition.

The Sun’s Reality…

Stenflo & Keller, Nature, **382**, 588 (1996)



Bommier & Molodij, A&A, **381**, 241 (2002)

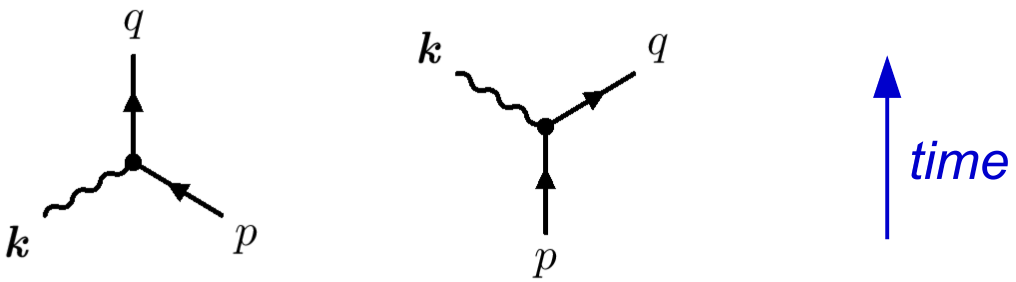


The spectral intensity of the Na I D doublet is evidently non-flat!

Atom-Photon Processes (1)

1st order: single-photon processes

- absorption and emission



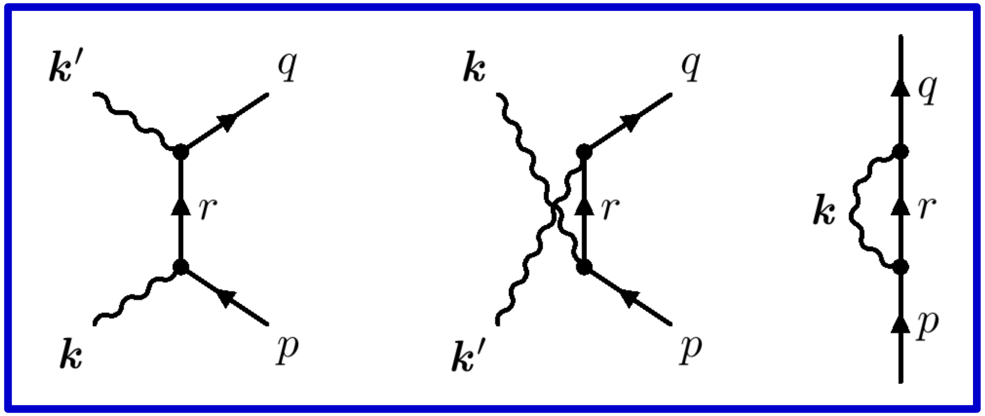
- applicable only in the CRD regime of line formation
  - non-coherent scattering (collision dominated and/or flat-spectrum radiation)

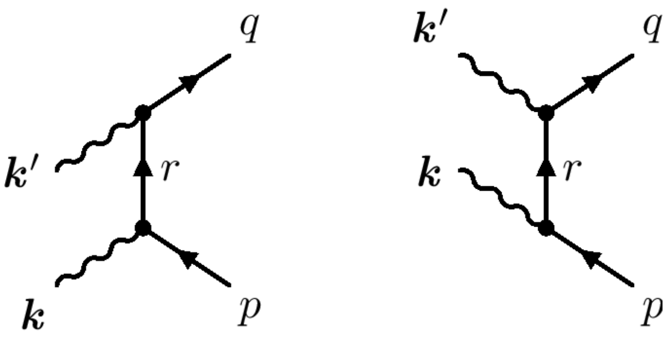
Atom-Photon Processes (2)

2

2^{nd} order: two-photon processes

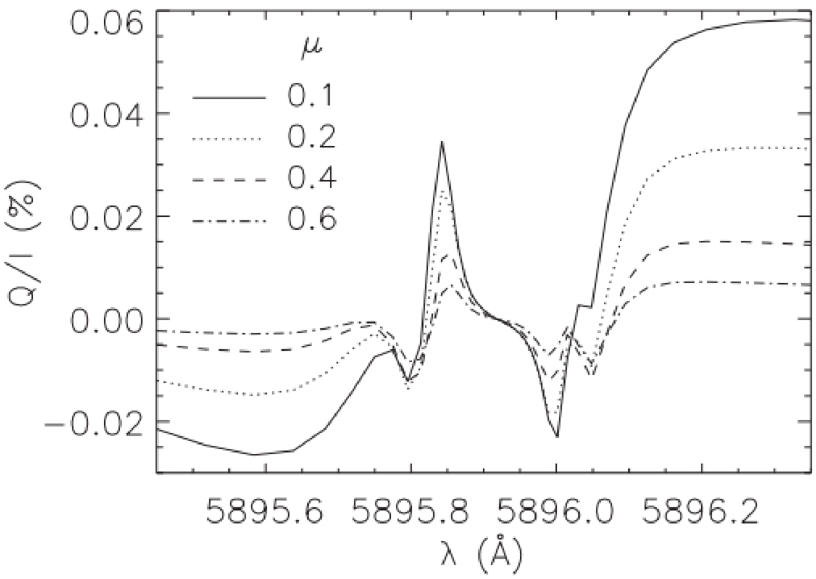
- coherent scattering; two-photon absorption; two-photon cascade



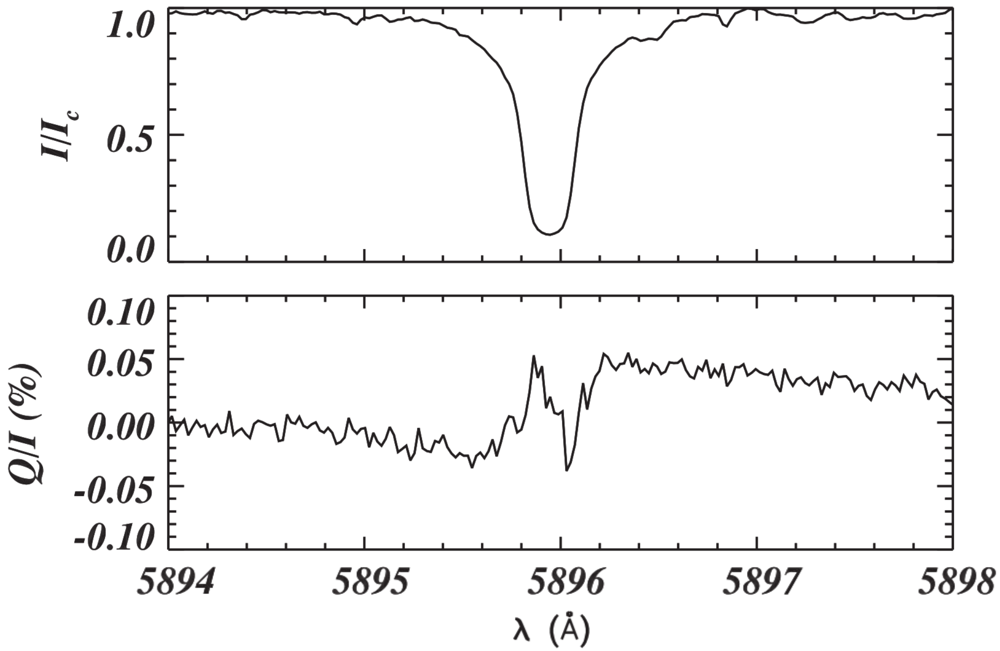


- applicable to the general case of PRD regime of line formation

Modeling Results with PRD and RT



Belluzzi, Trujillo Bueno, & Landi Degl'Innocenti, ApJ, **814**, 116 (2015)



J. Trujillo Bueno, SPW5, ASP Conf. Ser., **405,** 65 (2009)

Conclusions

- the current theory of scattering polarization in the limit of CRD is adequate for modeling polarized radiation scattering in a magnetized gas illuminated by a spectrally flat radiation
- the same QED formalism has been extended to also treat coherence effects in radiation scattering (PRD)
- polarized radiative transfer using realistic solar atmospheric models, including PRD effects, demonstrated that the peculiar polarization of Na I D_1 is without doubt of solar origin

Questions

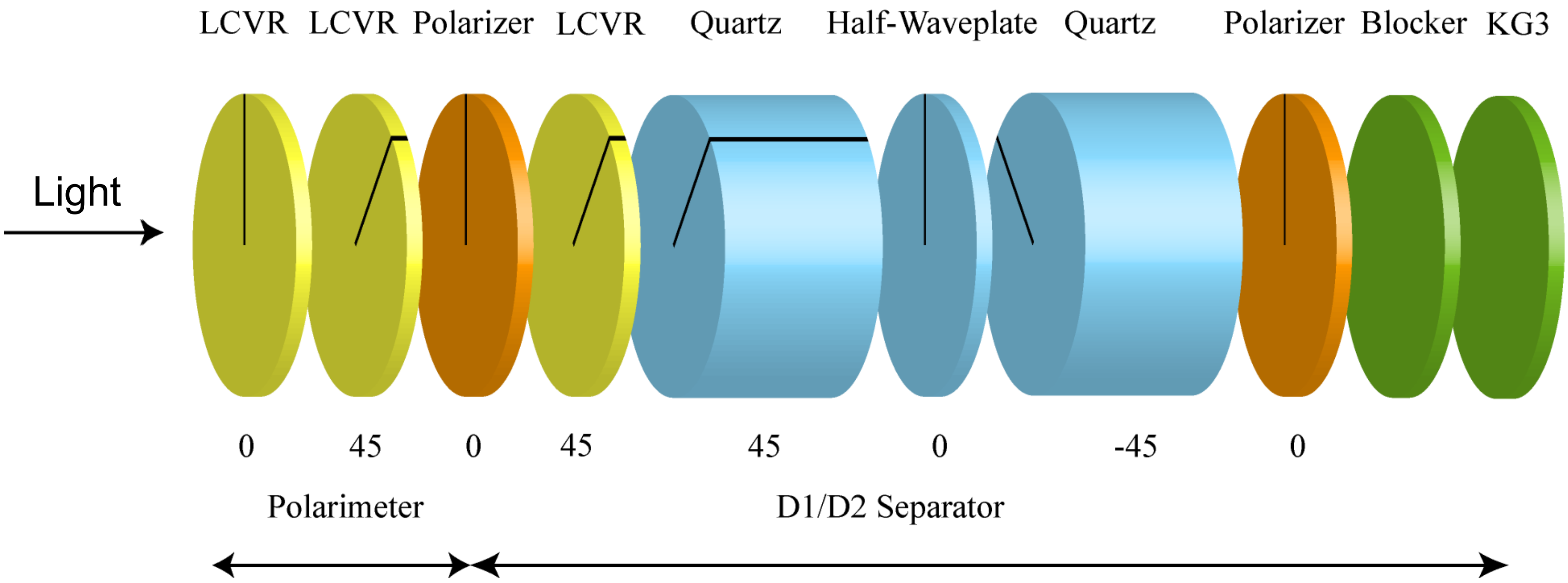
We dedicate this work to **Egidio Landi Degl'Innocenti** who was one of the promoters of the experiment, and a principal contributor to its interpretation.

Financial support for the experiment was provided by the National Center for Atmospheric Research, through the 2004 Director's Opportunity Funds.

We acknowledge the essential support of **G. Card** in the design and construction of the experiment. We have benefited from many discussions with several colleagues, who at times have also assisted in various aspects of the experiment. In particular, we thank **A. de Wijn, R. Manso Sainz, J. Trujillo Bueno, A. López Ariste, and J. O. Stenflo.**

Additional Slides

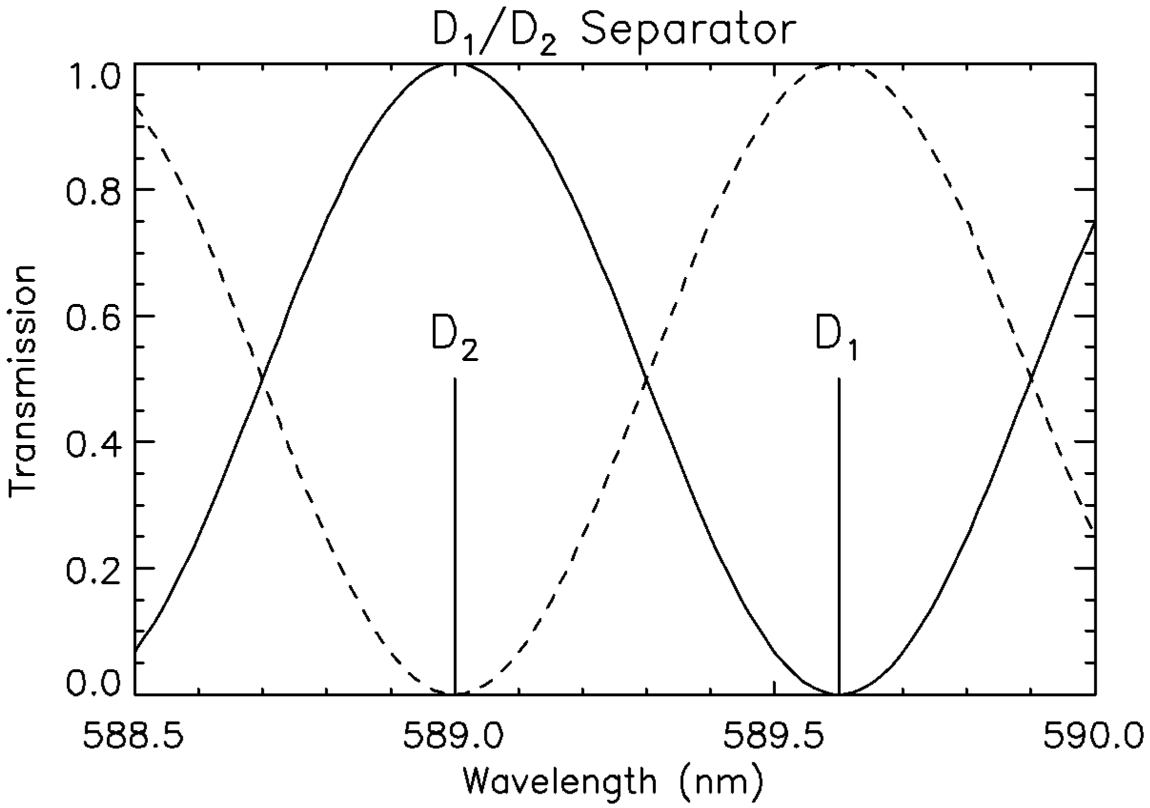
Stokes Analyzer



$\boldsymbol{S} = (I, Q, U, V)^T$ $\quad$ $\mathbf{R} \equiv$ Polarimeter Response Matrix

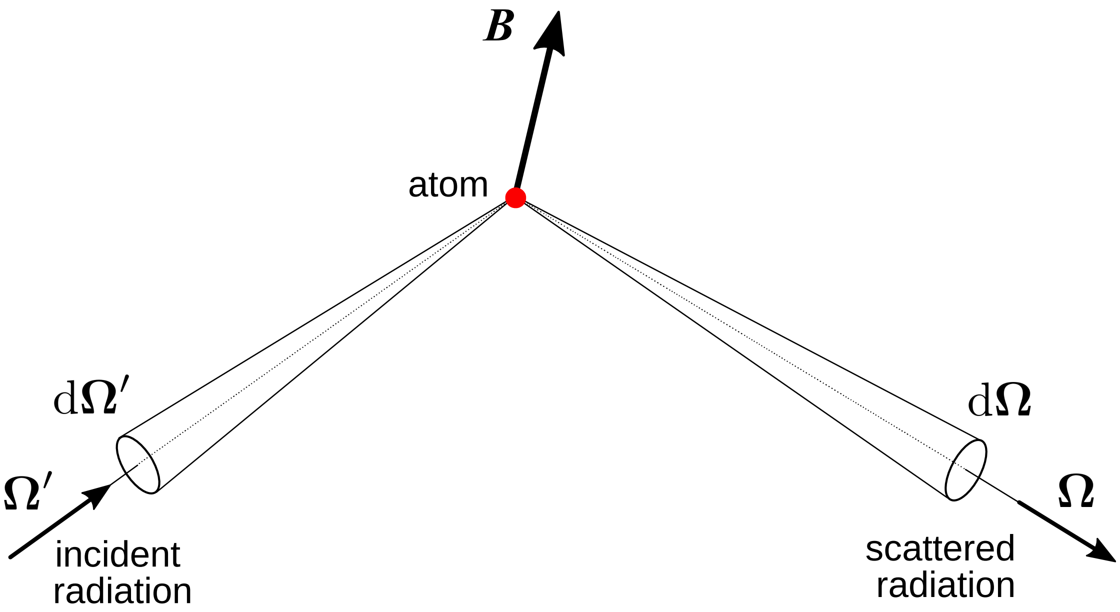
$$\boldsymbol{S}_{\text{input}} = \mathbf{R}^{-1}\, \boldsymbol{S}_{\text{meas}}$$

D-line Selection



NOTE: several of these “bandwidths” are sampled by the 9.5 nm bandpass of the KG3 filter, affecting the contribution of the background to the measured signal

Multi-Level Atom with HFS (1/2)



1) broadband polarized emissivity

$$\bar{\varepsilon}_i(\mathbf{\Omega}) = k_{\mathrm{L}}^{\mathrm{A}} \oint \frac{\mathrm{d}\mathbf{\Omega}'}{4\pi} \sum_{j=0}^{3} P_{ij}(\mathbf{\Omega},\mathbf{\Omega}';\boldsymbol{B})_{\mathrm{hfs}}\, S_j(\mathbf{\Omega}')\;, \qquad i=0,1,2,3$$

2) Hanle phase matrix

$$P_{ij}(\mathbf{\Omega},\mathbf{\Omega}';\boldsymbol{B})_{\mathrm{hfs}} = \sum_{KK'Q} (-1)^Q\, \mathcal{T}^K_Q(i,\mathbf{\Omega})\, \mathcal{T}^{K'}_{-Q}(j,\mathbf{\Omega}')\, W_{KK'Q}(J_\ell,J_u;\boldsymbol{B})_{\mathrm{hfs}}$$

Multi-Level Atom with HFS (2/2)

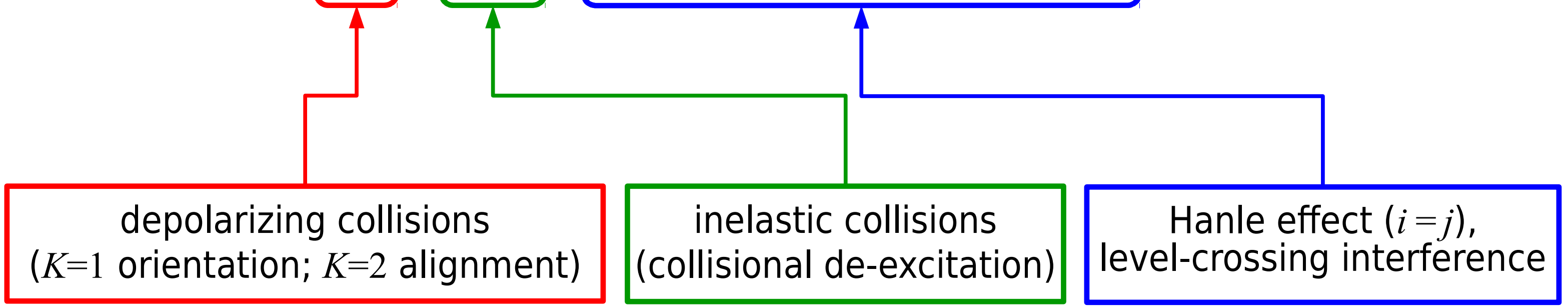
3) polarizability factor

$$W_{KK'Q}(J_\ell,J_u;\boldsymbol{B})_{\rm hfs}=\frac{3(2J_u+1)}{2I+1}\begin{Bmatrix}1&1&K\\J_u&J_u&J_\ell\end{Bmatrix}\begin{Bmatrix}1&1&K'\\J_u&J_u&J_\ell\end{Bmatrix}$$

$$\times\sum_{F_uF'_uF''_uF'''_u}\sqrt{(2K+1)(2K'+1)(2F_u+1)(2F'_u+1)(2F''_u+1)(2F'''_u+1)}\begin{Bmatrix}J_u&J_u&K\\F_u&F'_u&I\end{Bmatrix}\begin{Bmatrix}J_u&J_u&K'\\F''_u&F'''_u&I\end{Bmatrix}$$

$$\times\sum_{f_uf'_u}\sum_{ij}C^i_{F_u}(J_uf_u)\,C^i_{F''_u}(J_uf_u)\,C^j_{F'_u}(J_uf'_u)\,C^j_{F'''_u}(J_uf'_u)\begin{pmatrix}F_u&F'_u&K\\-f_u&f'_u&-Q\end{pmatrix}\begin{pmatrix}F''_u&F'''_u&K'\\-f_u&f'_u&-Q\end{pmatrix}$$

$$\times\left\{1+\boxed{\delta^{(K)}_{J_u}}+\boxed{\epsilon_{J_uJ_\ell}}+\boxed{\mathrm{i}[\omega_j(J_uf'_u)-\omega_i(J_uf_u)]/A_{J_uJ_\ell}}\right\}^{-1}$$



depolarizing collisions
(K=1 orientation; K=2 alignment)

inelastic collisions
(collisional de-excitation)

Hanle effect ($i=j$),
level-crossing interference

the coupling between $K'=2$ and $K=1$ is responsible for the so-called Alignment-to-Orientation (A-O) conversion mechanism

Atom-Photon Interaction

The atom+photon system is described by a statistical operator $\rho(t)$ evolving according to

$$\rho(t) = U(t,t_0)\rho(t_0)U^\dagger(t,t_0)$$

with formal solution for the evolution operator

$$U(t,t_0) = \sum_{n=0}^{\infty} \frac{(\mathrm{i}\hbar)^{-n}}{n!} \int_{t_0}^{t} \cdots \int_{t_0}^{t} d\tau_n \cdots d\tau_1 \, T\{H(\tau_n)\cdots H(\tau_1)\}$$

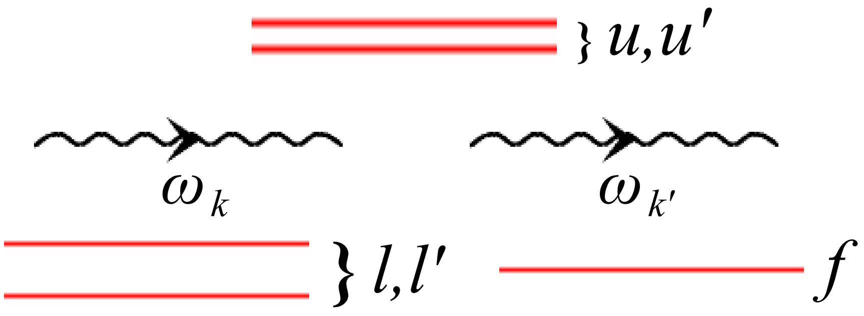
- This approach allows a diagrammatic treatment of atom-photon interaction
- Truncation order of solution expansion defines physical order of atom-photon processes

Partial Redistribution

Polarized RT Equation

Λ-type Multi-Term Atom

(no stimulated emission)



$$\frac{\mathrm{d}}{\mathrm{d}s}\boldsymbol{S} = -\mathbf{K}\,\boldsymbol{S} + \boldsymbol{\varepsilon} + \left[\boldsymbol{\varepsilon}^{(2)} - \boldsymbol{\varepsilon}^{(2)}_{\mathrm{s.p.}}\right]$$

$$\varepsilon_i^{(2)}(\omega_{k'},\hat{\boldsymbol{k}}') \equiv \frac{4}{3}\frac{e_0^4}{\hbar^2 c^4}\mathcal{N}\omega_{k'}^4 \sum_{ll'}\boxed{\rho_{ll'}}\sum_{uu'f}\sum_{qq'}\sum_{pp'}(-1)^{q'+p'}\,(r_q)_{ul}(r_{q'})^*_{u'l'}(r_p)_{u'f}(r_{p'})^*_{uf}$$

$$\times\sum_{KQ}\sum_{K'Q'}\sqrt{(2K+1)(2K'+1)}\begin{pmatrix}1 & 1 & K\\ -q & q' & -Q\end{pmatrix}\begin{pmatrix}1 & 1 & K'\\ -p & p' & -Q'\end{pmatrix}T^{K'}_{Q'}(i,\hat{\boldsymbol{k}}')$$

$$\times\,(\boxed{\epsilon_{uu'}}+\mathrm{i}\omega_{uu'})^{-1}\int_0^\infty d\omega_k\,\boxed{\mathcal{R}(\Omega_u,\Omega_{u'};\Omega_l,\Omega_{l'},\Omega_f;\omega_k,\omega_{k'},\Theta)}$$

$$\times\oint\frac{d\hat{\boldsymbol{k}}}{4\pi}\sum_{j=0}^{3}T^K_Q(j,\hat{\boldsymbol{k}})\,S_j(\omega_k,\hat{\boldsymbol{k}})$$

density matrix of initial state

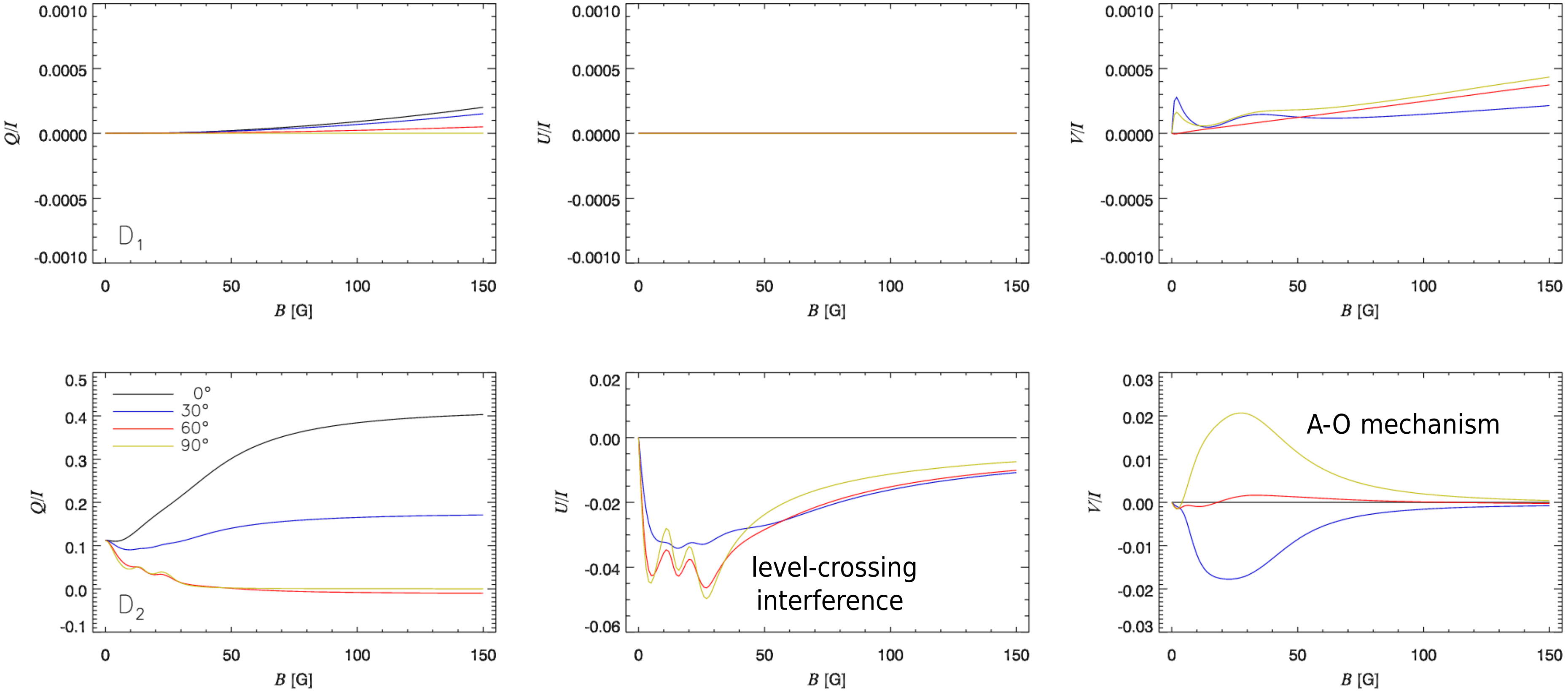
total inverse lifetime of upper state

redistribution function

Collisional Effects (1/3)

Modeling Results

(optically thin vapor, unpolarized input, no collisions)



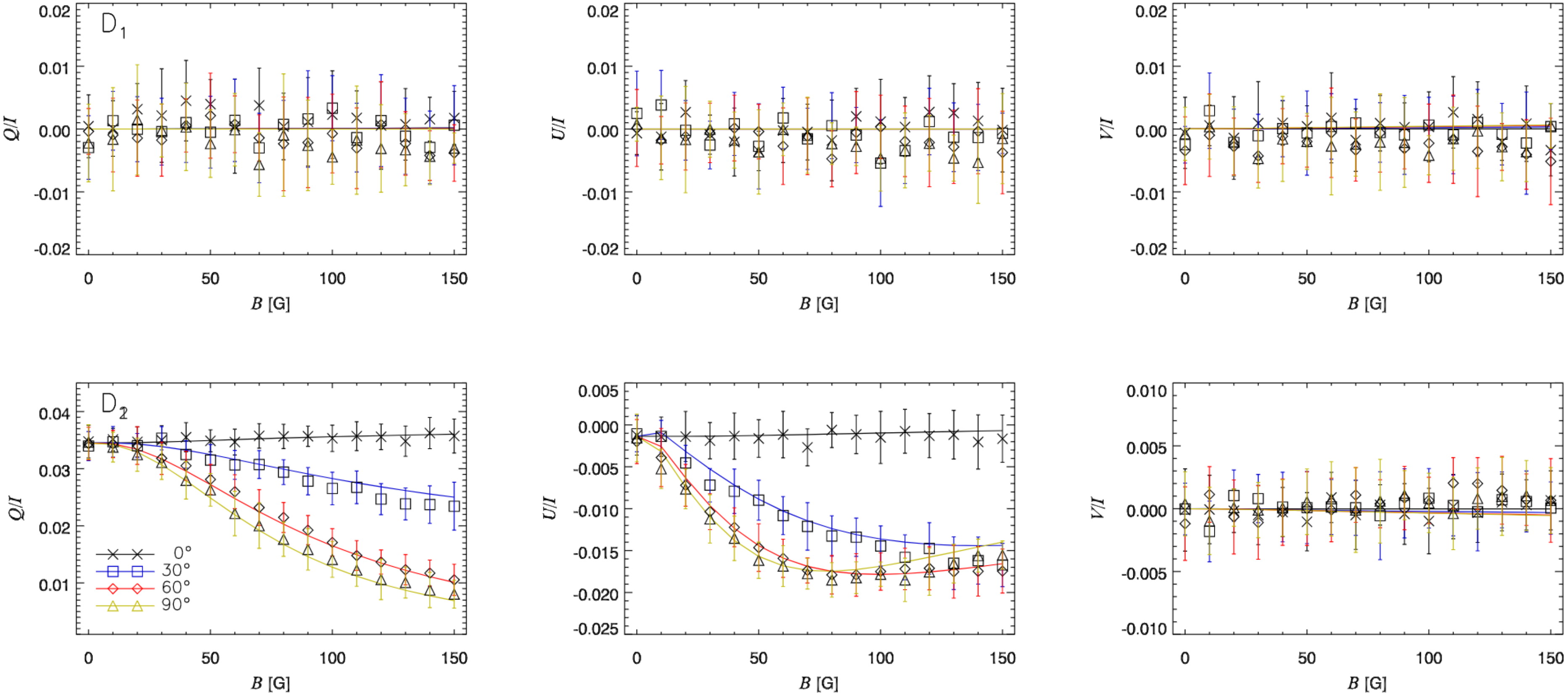
level-crossing interference

A-O mechanism

Collisional Effects (2/3)

Experimental Results (2017; old cell)

(optically thin vapor, no background radiation)

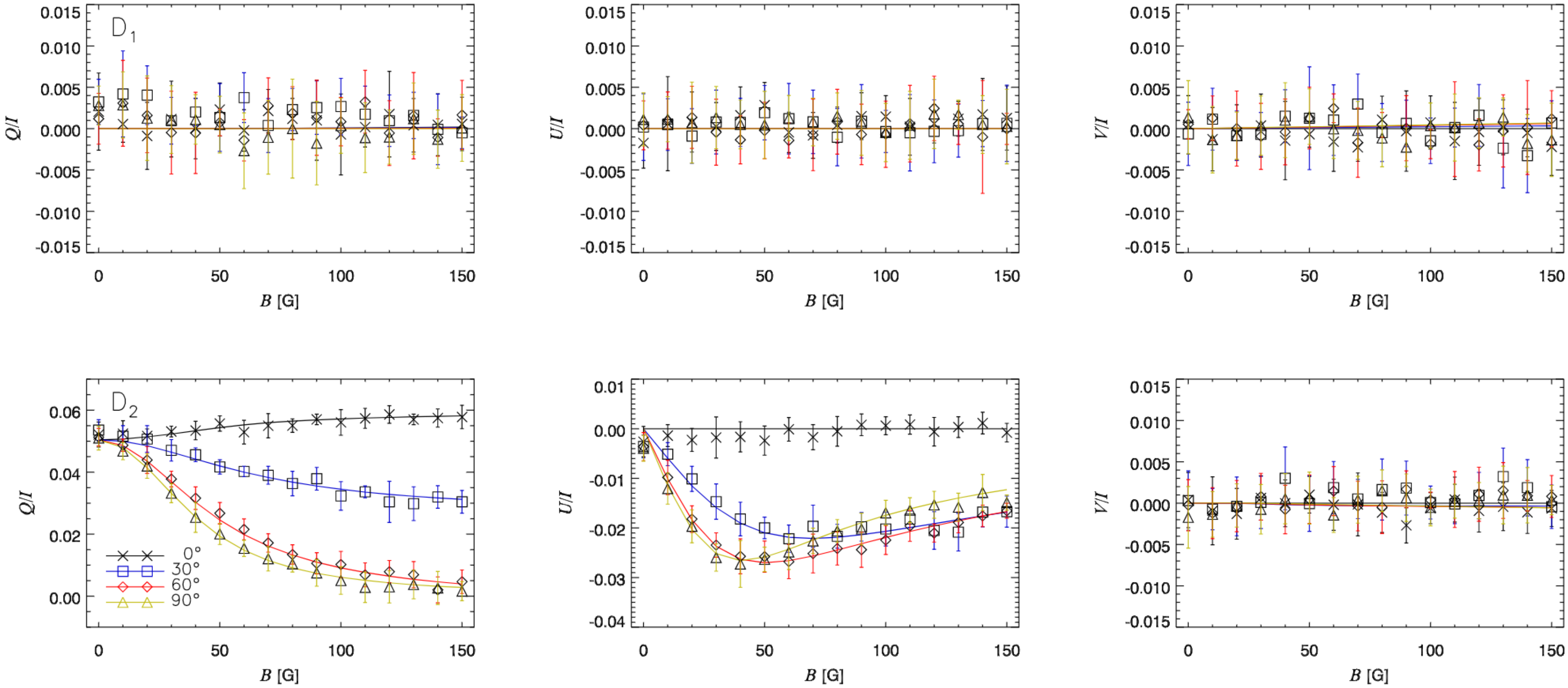


$\tau_{D2} \approx 0.1$, $\delta^{(2)} \approx 24$, $\epsilon \approx 1.6$

Collisional Effects (3/3)

Experimental Results (2017; new cell)

(optically thin vapor, no background radiation)



$\tau_{D2} \approx 0.1$, $\delta^{(2)} \approx 11$, $\epsilon \approx 0.94$