Scattering polarization diagnostics of coronal magnetism

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Why Spectro-Polarimetry?

- **polarization** of radiation is produced whenever the interaction of photons with ions is affected by **symmetry breaking** processes, e.g.,
  - presence of **magnetic and electric fields** interacting with the ions
  - **anisotropic excitation and de-excitation** (radiative and/or collisional) of the atomic levels
- interpretating the **spectral** and **polarization** properties of radiation allows us to diagnose **thermodynamic and electromagnetic processes** occurring in a plasma

Polarization of Radiation

- plane-wave solution of a radiation field (e.g., valid in the far-field approximation of a radiating dipole) of angular frequency ω propagating in the z direction

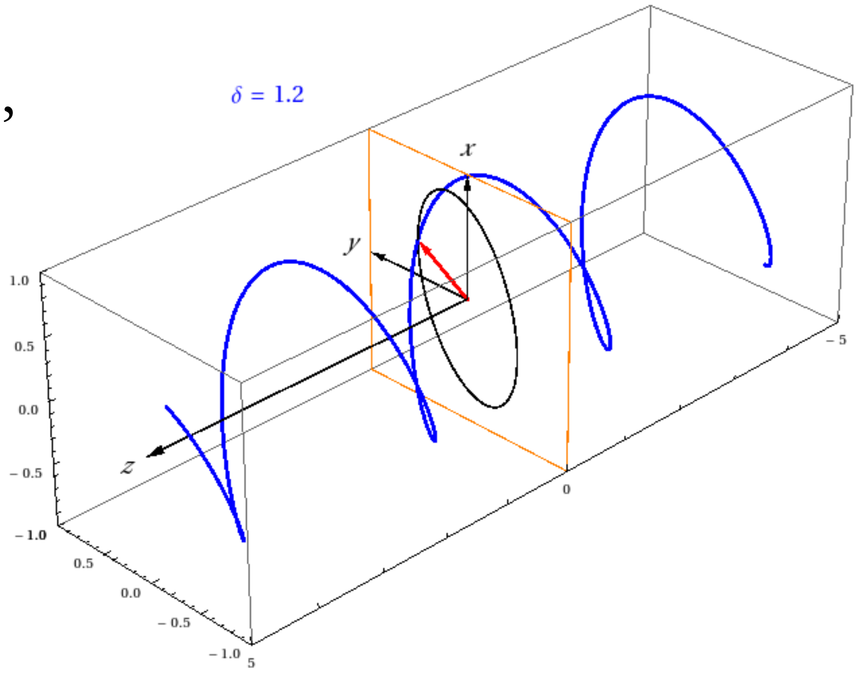
$$E_{x,y}(z,t,\omega) = A_{x,y}\, e^{i(kz-\omega t+\delta_{x,y})}\ , \qquad k=\omega/c$$

where $A_{x,y}$ and $\delta_{x,y}$ are **four real quantities**

- at any given value of z, as a function of time, the tip of the vector $\boldsymbol{E} \equiv (E_x, E_y)$ generally describes an ellipse (*polarization ellipse*)

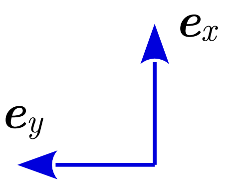
$$A_x = 0.8\ , \quad \delta_x = 1.2$$
$$A_y = 0.5\ , \quad \delta_y = 0.0$$

$$\delta \equiv \delta_x - \delta_y$$

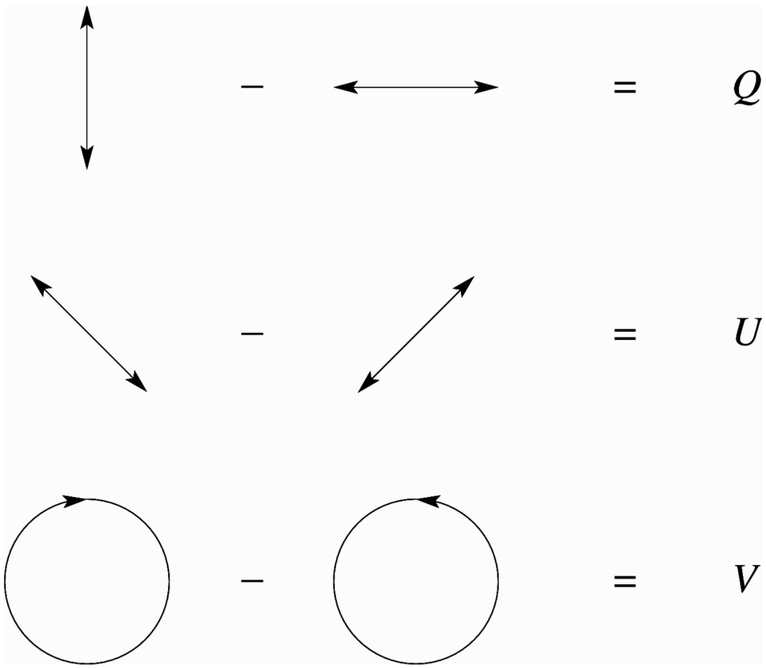


Operational Definition: Stokes Parameters

- wave amplitudes and phases are not immediately observable quantities, so we need to introduce **directly measurable signals**



$$
\begin{aligned}
I &= \langle E_x^* E_x \rangle + \langle E_y^* E_y \rangle \\
Q &= \langle E_x^* E_x \rangle - \langle E_y^* E_y \rangle \\
U &= \langle E_x^* E_y \rangle + \langle E_y^* E_x \rangle \\
V &= \mathrm{i}\langle E_x^* E_y \rangle - \mathrm{i}\langle E_y^* E_x \rangle
\end{aligned}
$$



$\langle \dots \rangle$ indicates averaging over the characteristic **temporal**, **spatial**, and **spectral** scales of the measurement

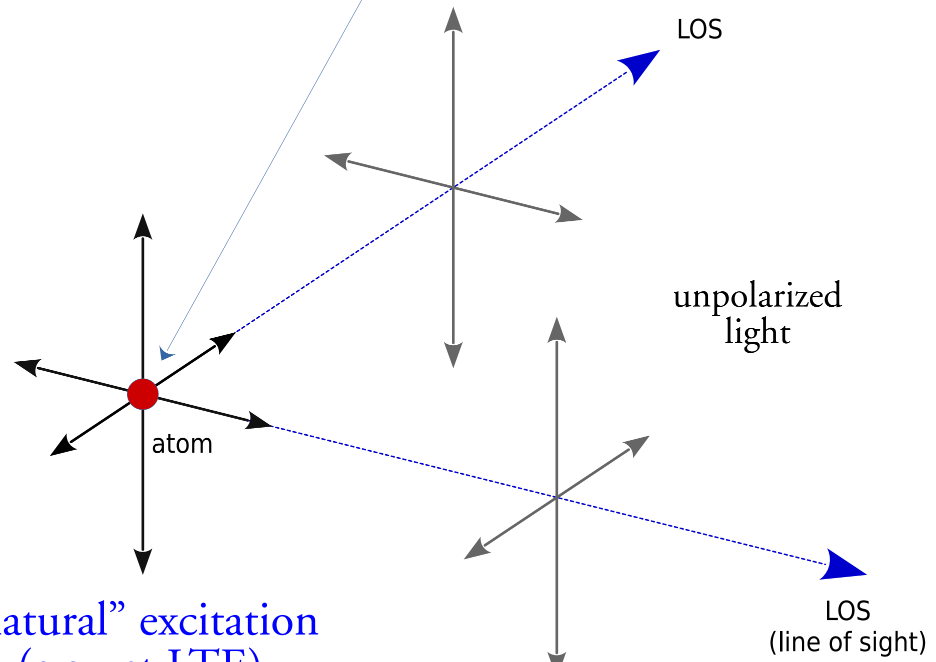
1: *Polarization in Spectral Lines*

Radiating Atom (semi-classical view): no field

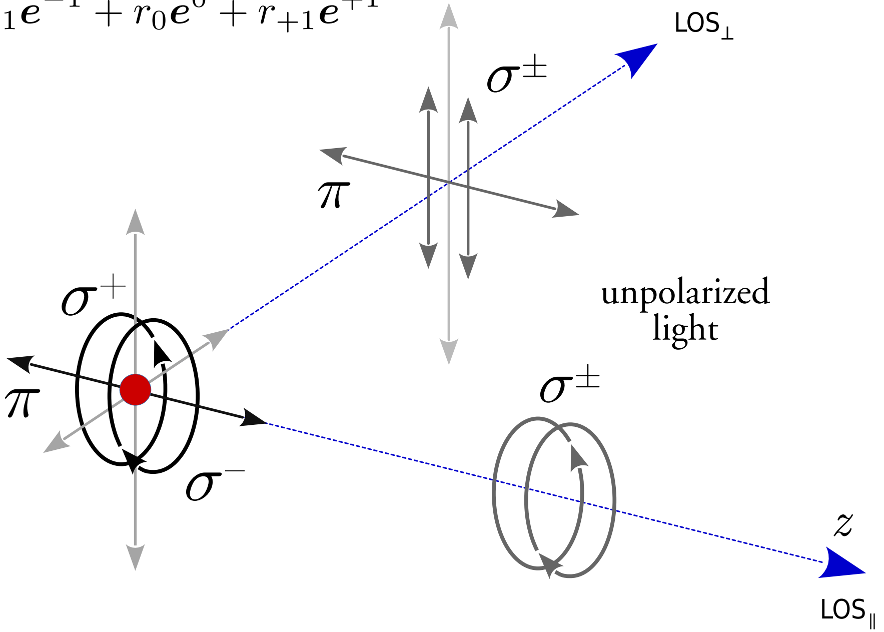
3D electron (damped) oscillator
(H. A. Lorentz, *The Theory of Electrons*, 1916)

$$\left.\begin{aligned} \boldsymbol{e}^{\pm 1} &= \mp\tfrac{1}{\sqrt{2}}(\boldsymbol{e}_x \mp \boldsymbol{e}_y) \\ \boldsymbol{e}^{0} &= \boldsymbol{e}_z \end{aligned}\right\}$$ ← spherical basis

$$\begin{aligned} \boldsymbol{r} &= x\boldsymbol{e}_x + y\boldsymbol{e}_y + z\boldsymbol{e}_z \\ &= r_{-1}\boldsymbol{e}^{-1} + r_0\boldsymbol{e}^{0} + r_{+1}\boldsymbol{e}^{+1} \end{aligned}$$



“natural” excitation
(e.g., at LTE)



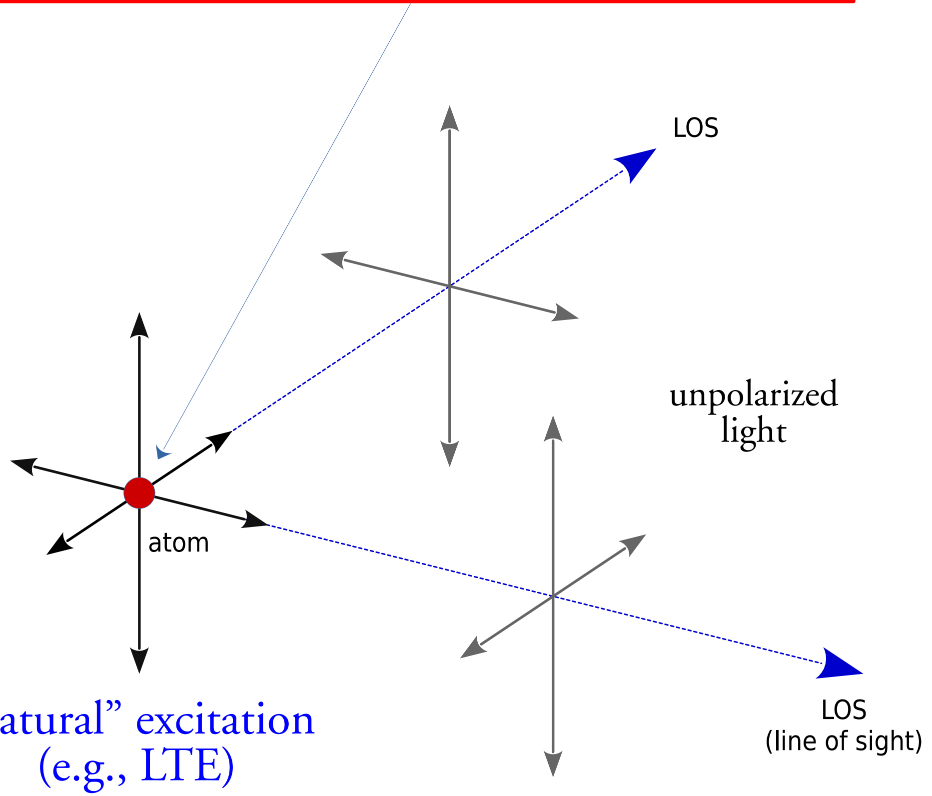
Zeeman Effect (semi-classical view)

3D electron (damped) oscillator
(H. A. Lorentz, *The Theory of Electrons*, 1916)

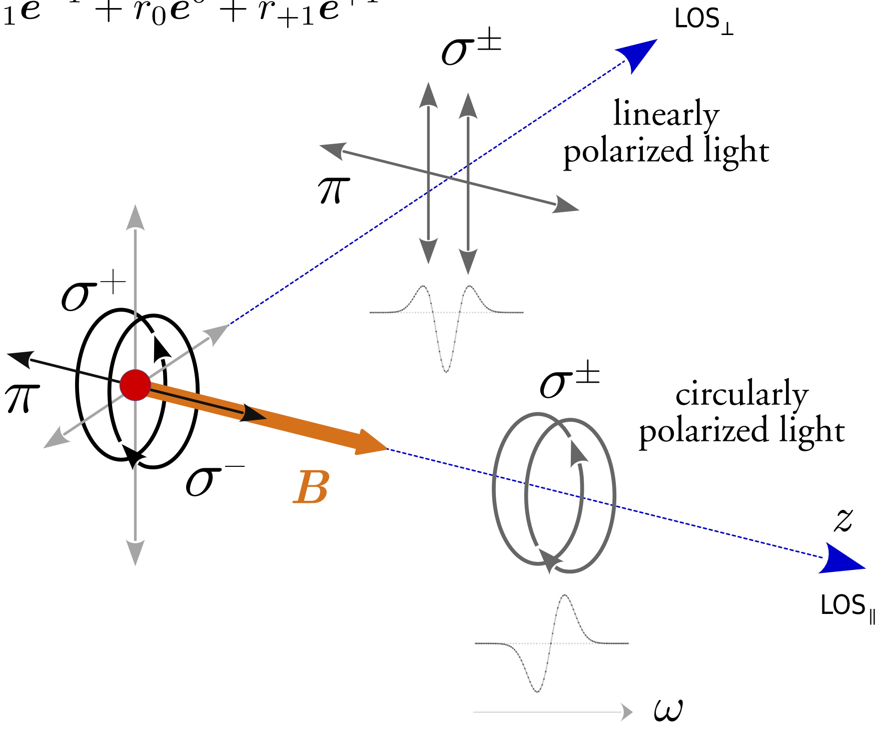
$$\boldsymbol{e}^{\pm 1} = \mp\frac{1}{\sqrt{2}}(\boldsymbol{e}_x \mp \boldsymbol{e}_y)$$
$$\boldsymbol{e}^{0} = \boldsymbol{e}_z$$

spherical basis

$$\boldsymbol{r} = x\boldsymbol{e}_x + y\boldsymbol{e}_y + z\boldsymbol{e}_z = r_{-1}\boldsymbol{e}^{-1} + r_0\boldsymbol{e}^{0} + r_{+1}\boldsymbol{e}^{+1}$$

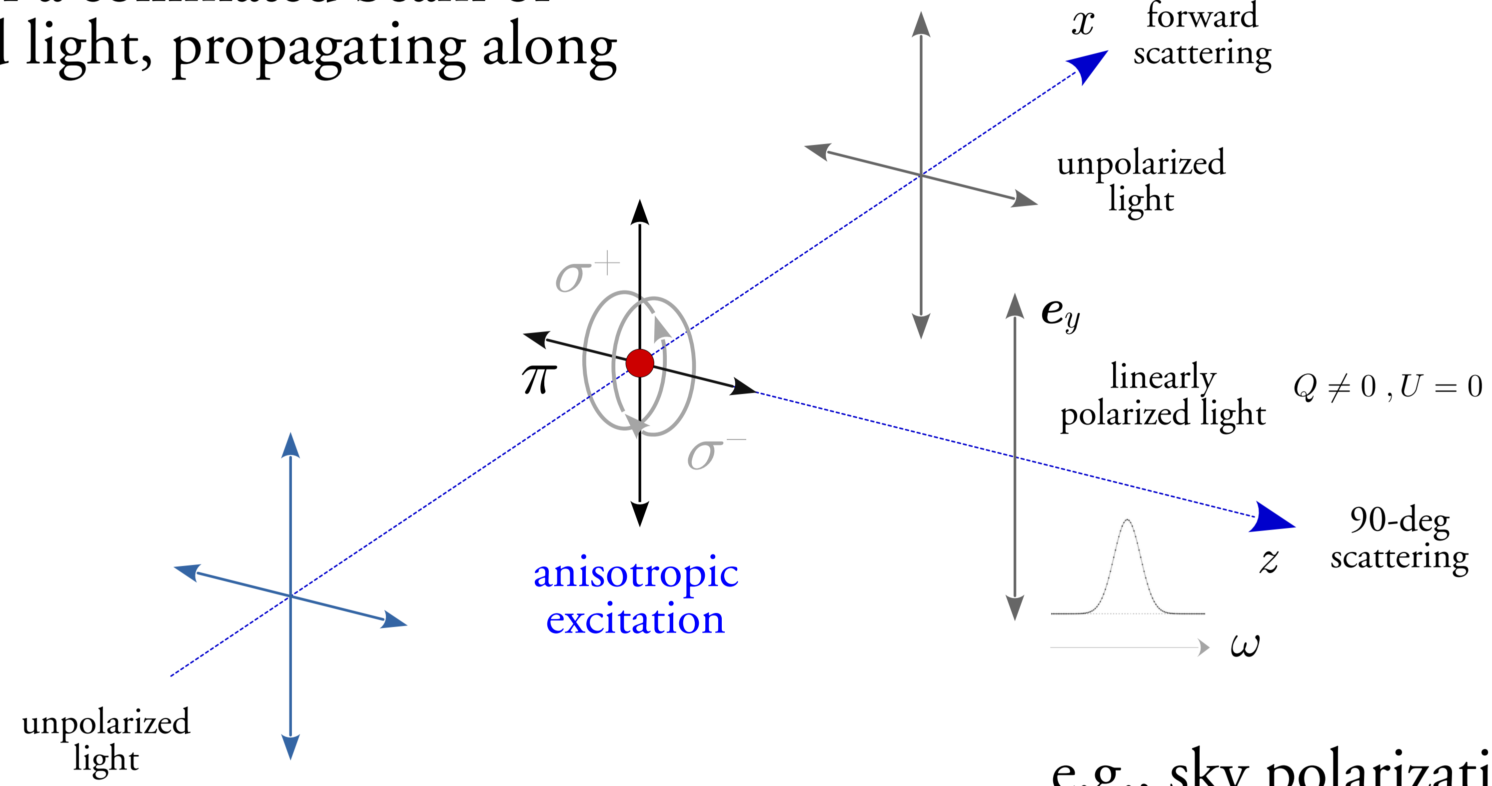


"natural" excitation
(e.g., LTE)



Scattering Polarization (semi-classical view)

scattering of a collimated beam of unpolarized light, propagating along the x-axis



e.g., sky polarization of Rayleigh-scattered sunlight

Atomic Polarization (semi-classical view)

90-deg scattering

$$E_x = \frac{1}{\sqrt{2}}(E_{-1} - E_{+1})$$

$$E_y = \frac{\mathrm{i}}{\sqrt{2}}(E_{-1} + E_{+1})$$

$$\longrightarrow$$

$$I = \langle E^*_{+1} E_{+1} \rangle + \langle E^*_{-1} E_{-1} \rangle$$
$$Q = -\langle E^*_{+1} E_{-1} \rangle - \langle E^*_{-1} E_{+1} \rangle$$
$$U = \mathrm{i}\langle E^*_{+1} E_{-1} \rangle - \mathrm{i}\langle E^*_{-1} E_{+1} \rangle$$
$$V = \langle E^*_{+1} E_{+1} \rangle - \langle E^*_{-1} E_{-1} \rangle$$

atomic *populations*

No polarization:
(e.g., natural excitation, no $\boldsymbol{B}$)

$$\langle E^*_{+1} E_{+1} \rangle = \langle E^*_{-1} E_{-1} \rangle$$
$$\langle E^*_{+1} E_{-1} \rangle = \langle E^*_{-1} E_{+1} \rangle = 0$$

atomic *coherences*

Q polarization; zero U, V:
(e.g., anisotropic excitation, no $\boldsymbol{B}$)

$$\langle E^*_{+1} E_{+1} \rangle = \langle E^*_{-1} E_{-1} \rangle$$
$$\langle E^*_{+1} E_{-1} \rangle = \langle E^*_{-1} E_{+1} \rangle \neq 0$$

Atomic Polarization (semi-classical view)

90-deg scattering

$$E_x = \frac{1}{\sqrt{2}}\left(E_{-1} - E_{+1}\right)$$

$$E_y = \frac{\mathrm{i}}{\sqrt{2}}\left(E_{-1} + E_{+1}\right)$$

$$\longrightarrow$$

$$\begin{aligned} I &= \langle E^*_{+1} E_{+1}\rangle + \langle E^*_{-1} E_{-1}\rangle \\ Q &= -\langle E^*_{+1} E_{-1}\rangle - \langle E^*_{-1} E_{+1}\rangle \\ U &= \mathrm{i}\langle E^*_{+1} E_{-1}\rangle - \mathrm{i}\langle E^*_{-1} E_{+1}\rangle \\ V &= \langle E^*_{+1} E_{+1}\rangle - \langle E^*_{-1} E_{-1}\rangle \end{aligned}$$

No polarization:
(e.g., natural excitation, no $\boldsymbol{B}$)

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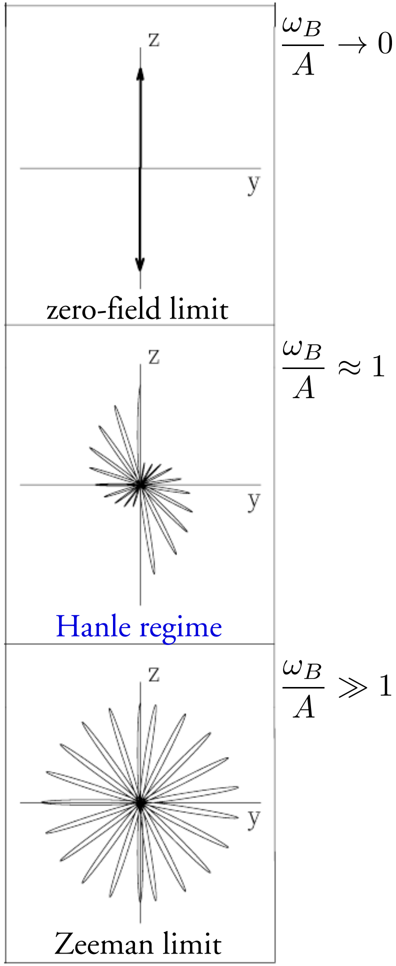
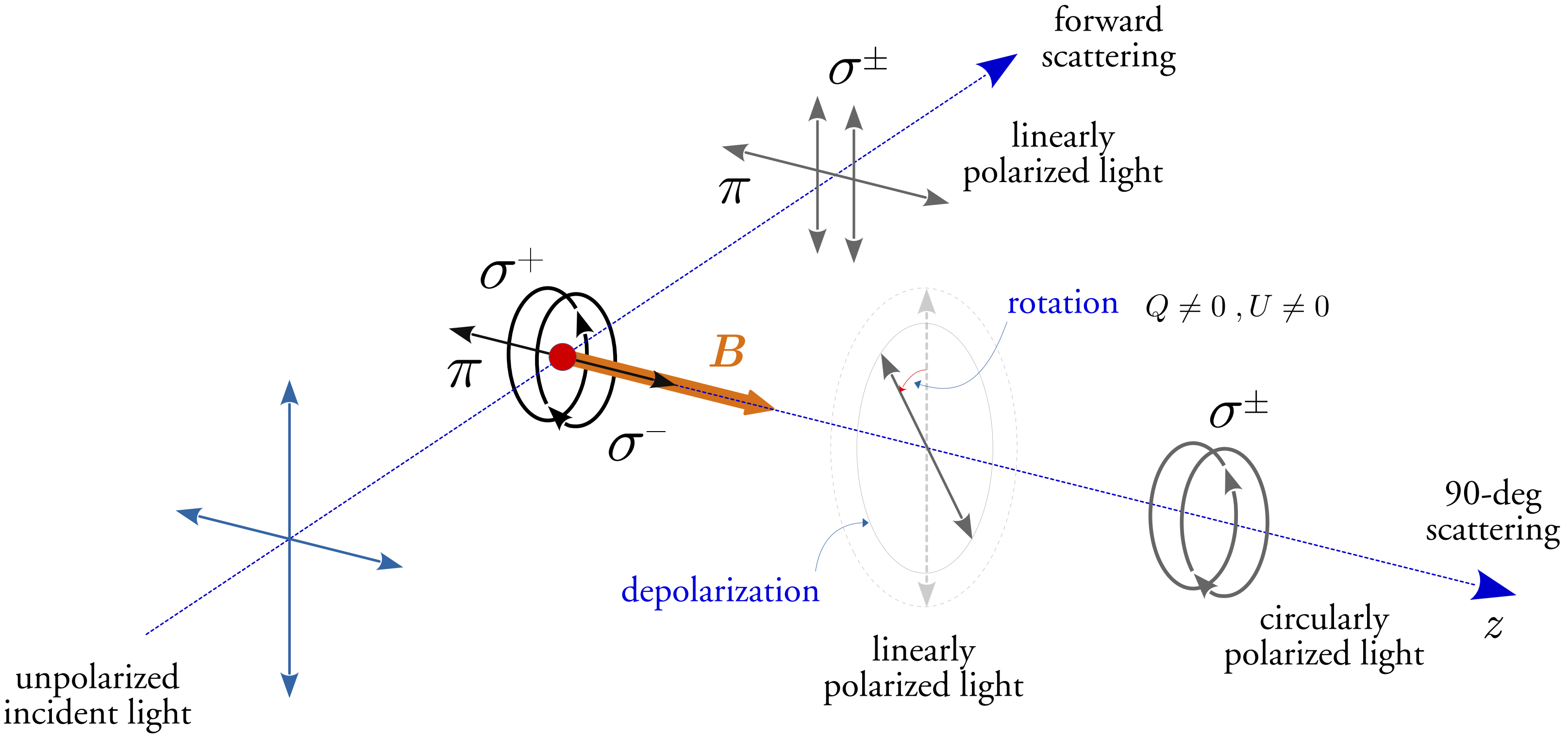
$$\langle E^*_{+1} E_{+1}\rangle = \langle E^*_{-1} E_{-1}\rangle$$
$$\langle E^*_{+1} E_{-1}\rangle = \langle E^*_{-1} E_{+1}\rangle \neq 0$$

scattering polarization is a manifestation of atomic *coherence*

Hanle Effect (semi-classical view)

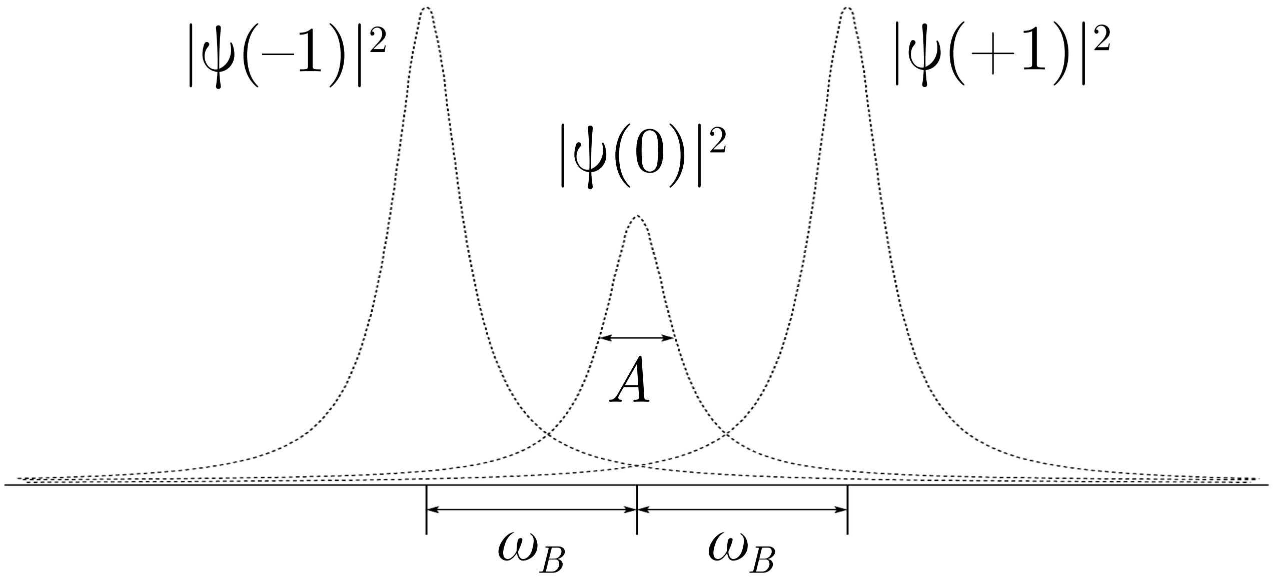


(from Landi Degl'Innocenti & Landolfi 2004)



rotation of plane of polarization implies the appearance of $U \neq 0$

Hanle Effect ("quantistic" view)



$$|\psi(M) + \psi(M')|^2 \neq |\psi(M)|^2 + |\psi(M')|^2$$

$$|\psi(M) + \psi(M')|^2 \to |\psi(M)|^2 + |\psi(M')|^2 \quad \text{when} \quad \omega_B \gg A$$

NLTE of the 2nd Kind

- **for zero fields**, a spectral line can be polarized only if the **weights** of the Zeeman components (i.e., the **populations** of their initial levels) are different
- **anisotropic excitation/de-excitation processes** (radiative and/or collisional) in stellar atmospheres create ***atomic polarization***, i.e., **population imbalance** and **quantum coherence** among atomic levels
- in contrast, atomic polarization is **relaxed or destroyed by isotropic processes**
  - e.g., the "thermalization" of atomic level populations (which consequent destruction of quantum coherence) in collisionally dominated plasmas (a typical LTE condition)
  - depolarization by a microscopically turbulent external field

→ **zero-field polarization** is characteristic of **low-density and anisotropically illuminated** plasmas (e.g., the solar chromosphere and corona)

Example: Solar Atmosphere

competing effects of **anisotropic irradiation** and **isotropic collisions**

- **photosphere**: radiation anisotropy is low; collision isotropy is high; collisional rates (gas density) is high → LTE conditions

→ zero-field polarization is **negligible**

- **chromosphere**: radiation anisotropy may be large (mostly dependent on CLV and horizontal plasma inhomogeneity); collision isotropy is high; collisional rates decrease quickly with height

→ zero-field polarization is **important**

- **corona**: radiation anisotropy is dominant (from both CLV and height); collision isotropy starts to break down; collisional rates are low

→ zero-field polarization is **dominant**

2. *Fundamentals of Spectral Line Formation*

Radiative Transfer

let us consider the (scalar) Radiative Transfer Equation (RTE), describing the variation of the **radiation intensity** at a point of linear coordinate s along the ray path, and around the resonance frequency ω_{ul} of an atomic transition between an upper level u and a lower level l :

$$\frac{\mathrm{d}}{\mathrm{d}t}\frac{I(\omega)}{c} \equiv \frac{\mathrm{d}}{\mathrm{d}s} I(\omega) = -k(\omega)I(\omega) + \varepsilon(\omega) \; , \qquad \omega = 2\pi c/\lambda$$

$$\varepsilon(\omega) = \frac{\hbar\omega}{4\pi} N_u \, A_{ul} \, \phi(\omega - \omega_{ul}) \quad \leftarrow \text{ emission coefficient}$$

$$k(\omega) = \frac{\hbar\omega}{4\pi} N_l \, B_{lu} \, \phi(\omega - \omega_{ul}) \quad \leftarrow \text{ absorption coefficient}$$

Radiative Transfer

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$$\varepsilon(\omega) = \frac{\hbar\omega}{4\pi} N_u A_{ul} \, \phi(\omega - \omega_{ul})$$

$$k(\omega) = \frac{\hbar\omega}{4\pi} N_l \, B_{lu} \, \phi(\omega - \omega_{ul})$$

level population (**unknown**) → N_u

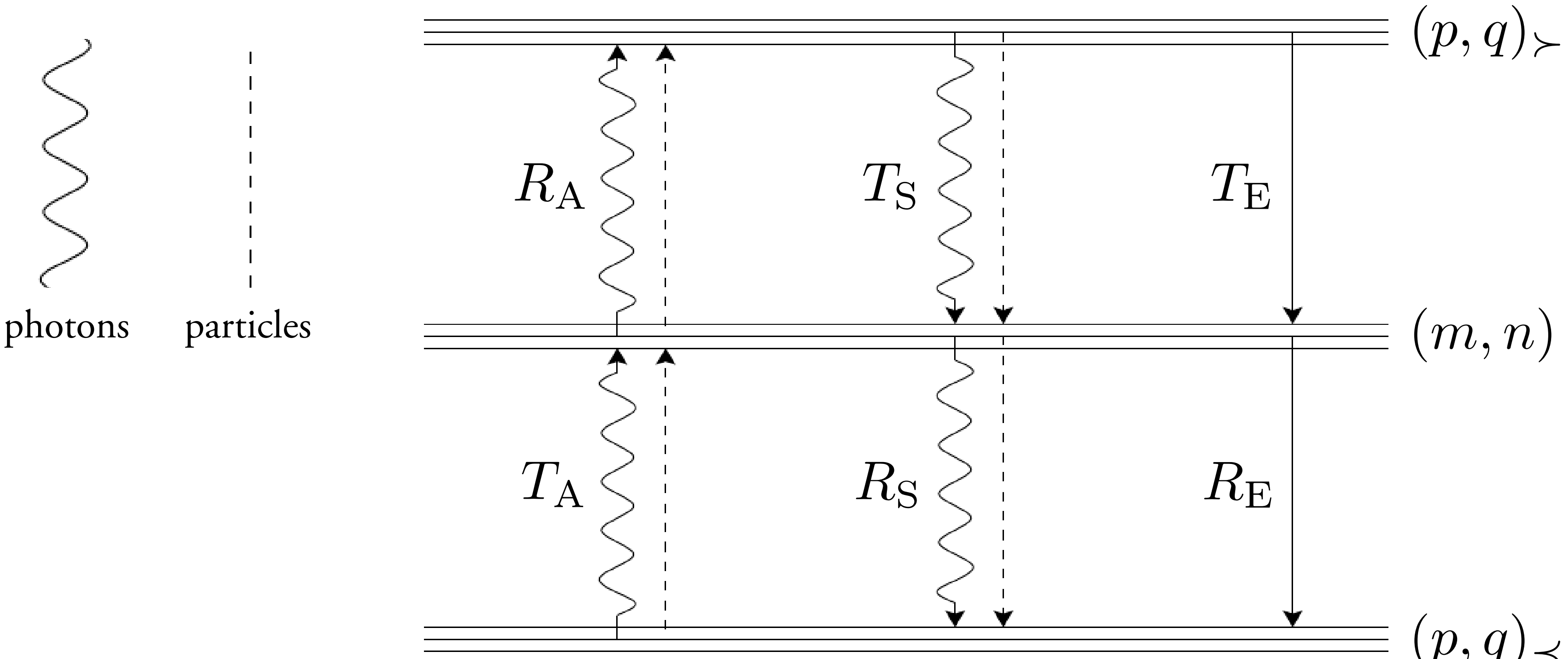
photon energy → $\hbar\omega$

transition probability → A_{ul}

line profile → $\phi(\omega - \omega_{ul})$

Statistical Equilibrium

in a multi-level system, a given set of levels (m,n) is subject to both **transfer** (T) processes **from** and **relaxation** (R) processes **towards** other levels



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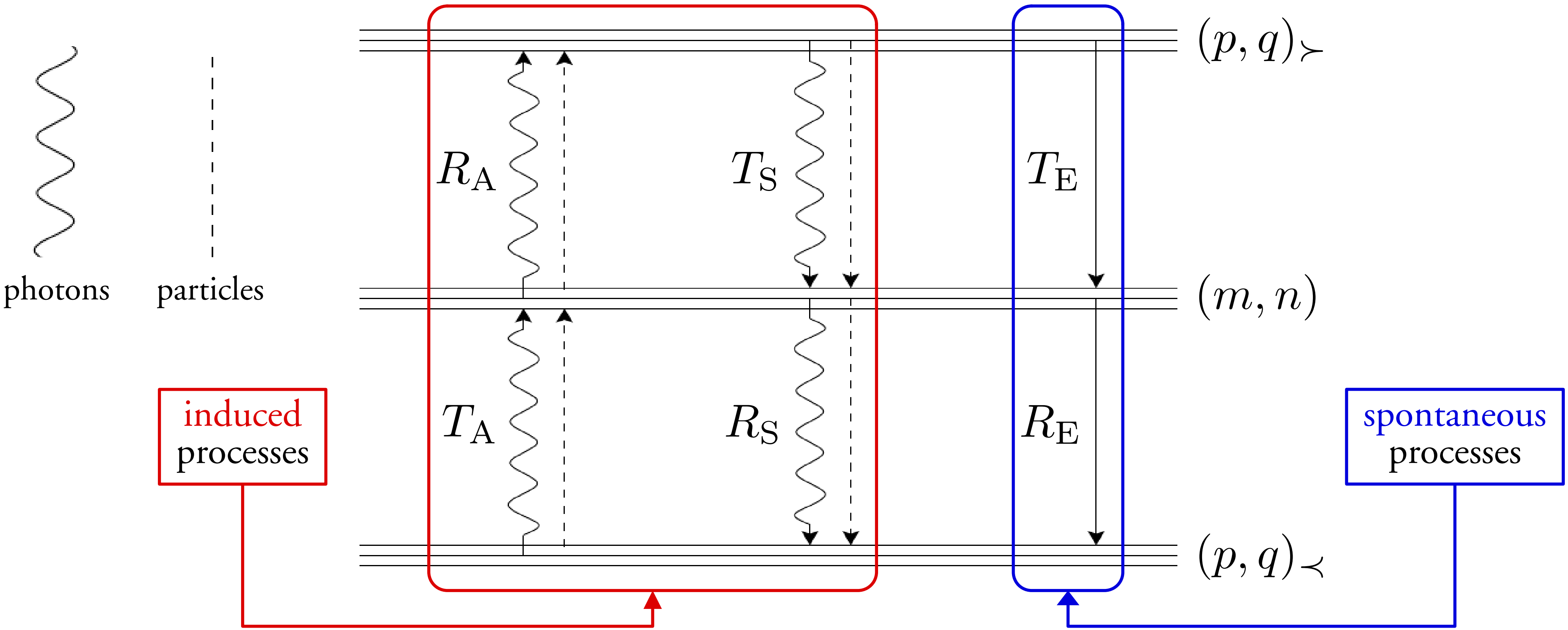
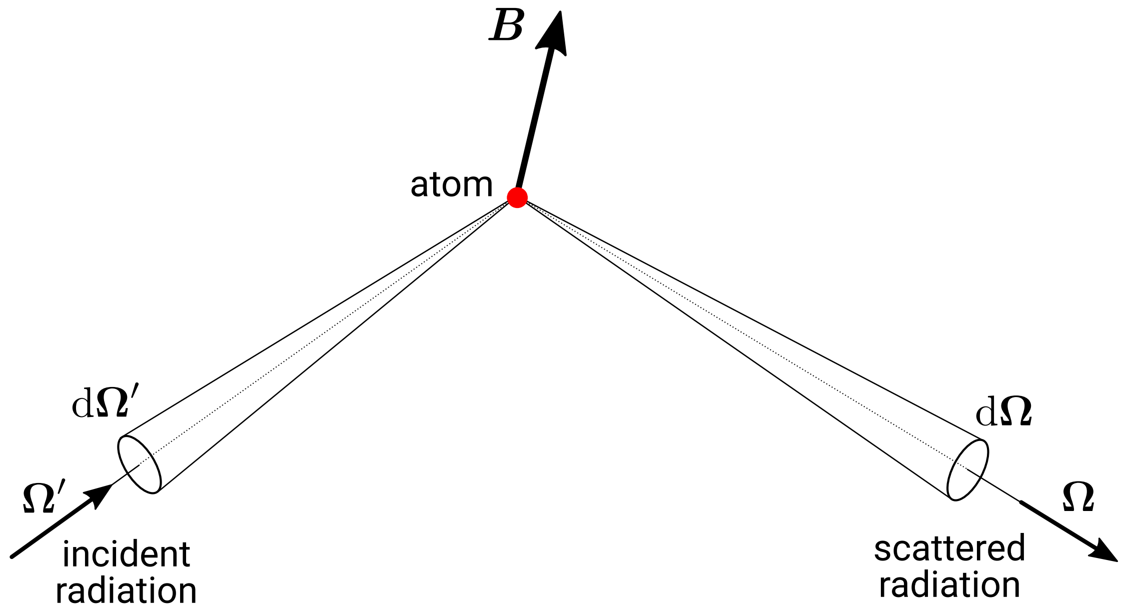


Scattering of Radiation



- in the 1st-order approximation of light-matter interaction, radiation scattering is treated as the **incoherent** sequence of photon absorption and re-emission (CRD)
- the upper-level population N_u is the solution of the SE of the 2-level atom illuminated by the incident radiation

3: *Hanle-Effect Diagnostics of Coronal Magnetism*

Radiation Drivers of Scattering Polarization

- we consider the simplest scenario:
  - the specific intensity of the solar surface is only a function of $\mu = \cos\vartheta$ (e.g., center-to-limb variation; CLV)
  - the **cylindrical symmetry** of the **unpolarized** radiation around the local vertical through the scattering point allows us to fully describe the radiation field using only the two **radiation tensor** components $\underbrace{J^0_0(\omega),\, J^2_0(\omega)}$

    irreducible spherical tensors

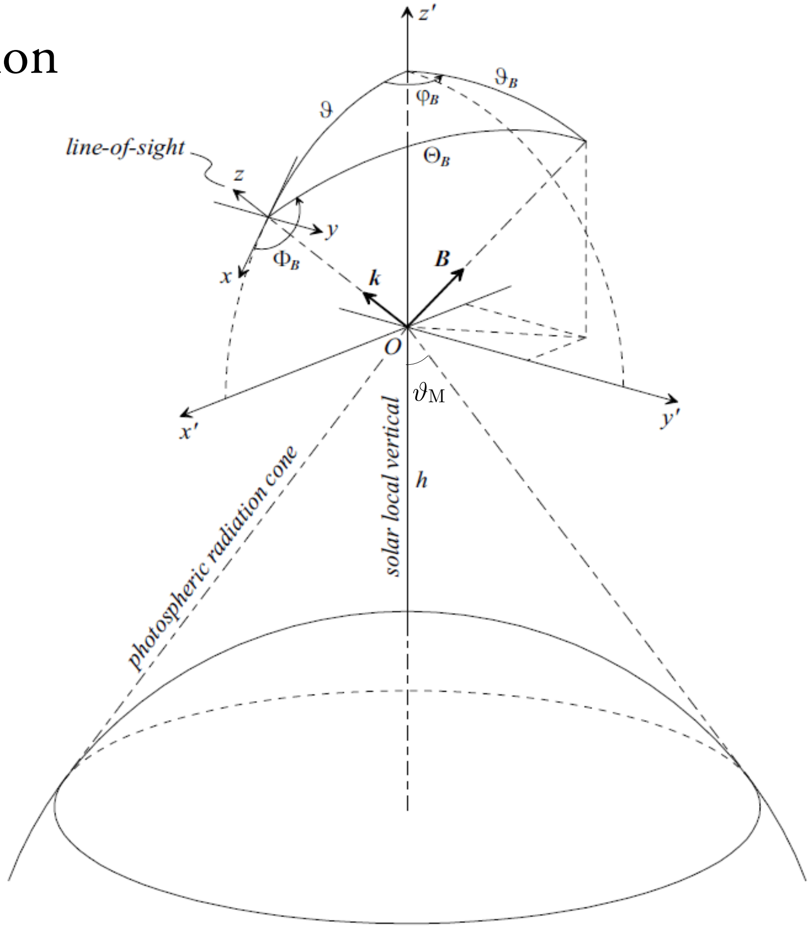
- if we can neglect CLV:

$$J^0_0(\omega) = \tfrac{1}{2}(1 - \cos\vartheta_{\rm M})\, I(\omega)$$ **dilution factor**

$$J^2_0(\omega) = \frac{1}{4\sqrt{2}} \sin^2\!\vartheta_{\rm M} \cos\vartheta_{\rm M}\, I(\omega)$$ **anisotropy factor**

radiation anisotropy

$$w(\omega, \vartheta_{\rm M}) \equiv \sqrt{2}\, \frac{J^2_0(\omega)}{J^0_0(\omega)} = \tfrac{1}{2}(1 + \cos\vartheta_{\rm M}) \cos\vartheta_{\rm M}$$



Hanle Effect: Scattering Emissivity (1)

- in the presence of processes that polarize the atom (e.g., the anisotropic illumination of the plasma), the **population** N_u of the excited state J_u is replaced by its **density matrix**
- we assume that the lower level J_l is unpolarized (easier to get a closed solution)
- if we can ignore to first order any energy splitting of the levels in the line profile (the so-called "Hanle limit" when a magnetic field is present), then the following generalization holds true

$$\varepsilon(\omega) = \frac{\hbar\omega}{4\pi} N_u A_{J_u J_l}\, \phi(\omega - \omega_{ul})$$

$$\rightarrow \ \varepsilon_i(\omega, \hat{\boldsymbol{k}}) = \frac{\hbar\omega}{4\pi} N_u A_{J_u J_l}\, \phi(\omega - \omega_{ul}) \sum_{KQ} w^{(K)}_{J_u J_l} \boxed{\sigma^K_Q(J_u)\, \mathcal{T}^K_Q(i, \hat{\boldsymbol{k}})} \qquad (i = 0, 1, 2, 3)$$

reference-frame dependent quantities

$$K = 0, \ldots, \min(J_u, 2)$$

$$Q = -K, \ldots, +K$$

space invariance requires that sum over Q is conserved under frame transformation

$\hat{\boldsymbol{k}} \equiv$ direction of the LOS

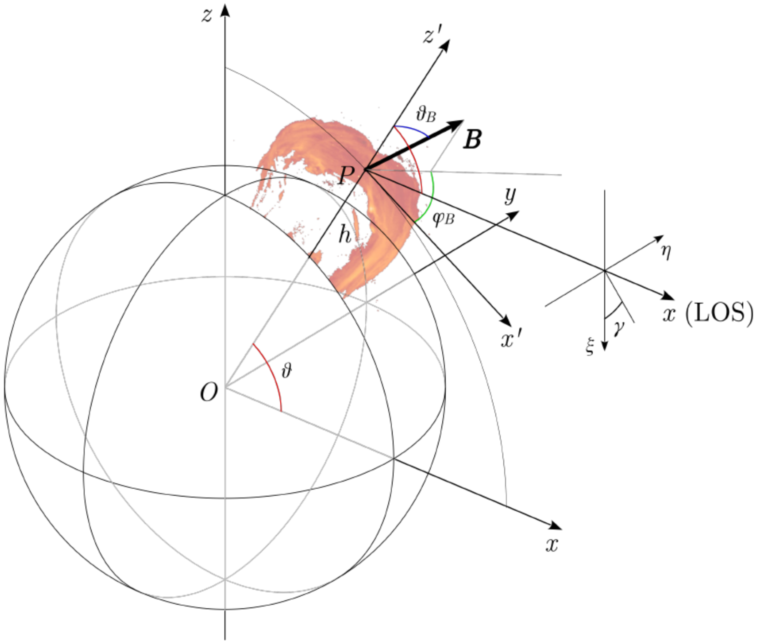
$w^{(K)}_{J_u J_l} \equiv$ transition *polarizability* of order K

$\sigma^K_Q(J_u) \equiv$ normalized density matrix (*atomic polarization*)

$\mathcal{T}^K_Q(i; \hat{\boldsymbol{k}}) \equiv$ polarization tensors (Landi Degl'Innocenti 1983)

Hanle Effect: Scattering Emissivity (2)

- for the 2-level atom (J_u, J_l) with unpolarized lower level, we can provide a dimensionless expression of the polarized scattering emissivity in the presence of a magnetic field $\boldsymbol{B}$, integrated over the line profile
  - because the circular polarization vanishes when integrated across the line, this expression only applies to the **intensity and linear polarization**



$$\varepsilon_i(\hat{\boldsymbol{k}}) \propto \sum_{KQ} w^{(K)}_{J_u J_l} \left[\frac{w^{(K)}_{J_u J_l}}{1 + \mathrm{i}\, Q\, g_{J_u} \omega_B / A_{J_u J_l}} d^K_{0Q}(\vartheta_B) \frac{J^K_0(\omega_{ul})}{J^0_0(\omega_{ul})} \right] \times \left[\sum_P \mathrm{e}^{-\mathrm{i} P \varphi_B} d^K_{PQ}(\vartheta_B) \mathcal{T}^K_P(i;\vartheta,\gamma) \right] \qquad (i = 0, 1, 2)$$

B-frame

$g_{J_u} \equiv$ Landé factor

$d^K_{PQ}(\beta) \equiv$ reduced rotation matrix

$\mathcal{T}^K_P(i;\vartheta,\gamma) \equiv$ polarization tensors in the local-vertical frame

Hanle Effect: Scattering Emissivity (3)

- for the 2-level atom (J_u, J_l) with unpolarized lower level, we can provide a dimensionless expression of the polarized scattering emissivity in the presence of a magnetic field $\boldsymbol{B}$, integrated over the line profile
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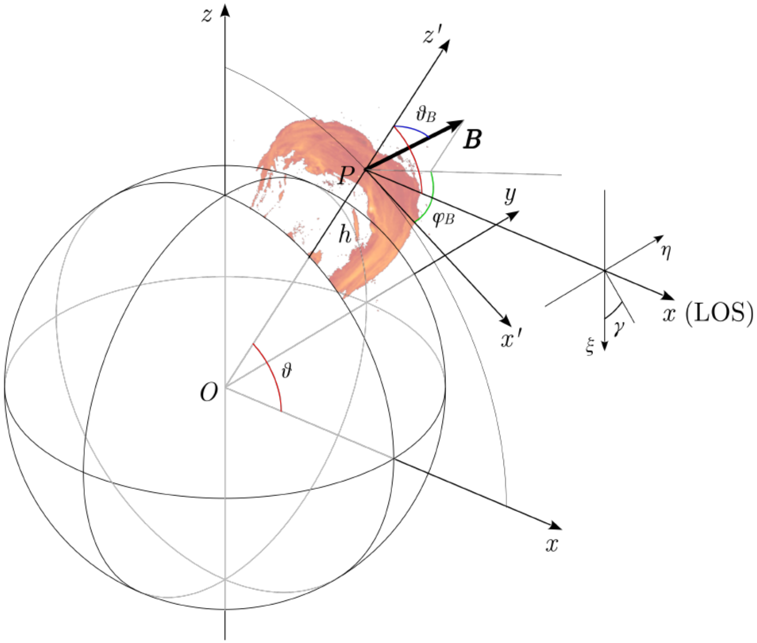

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Hanle-effect denominator

polarization tensors in the B-frame

radiation tensors in the B-frame

Relaxation of Atomic Coherences

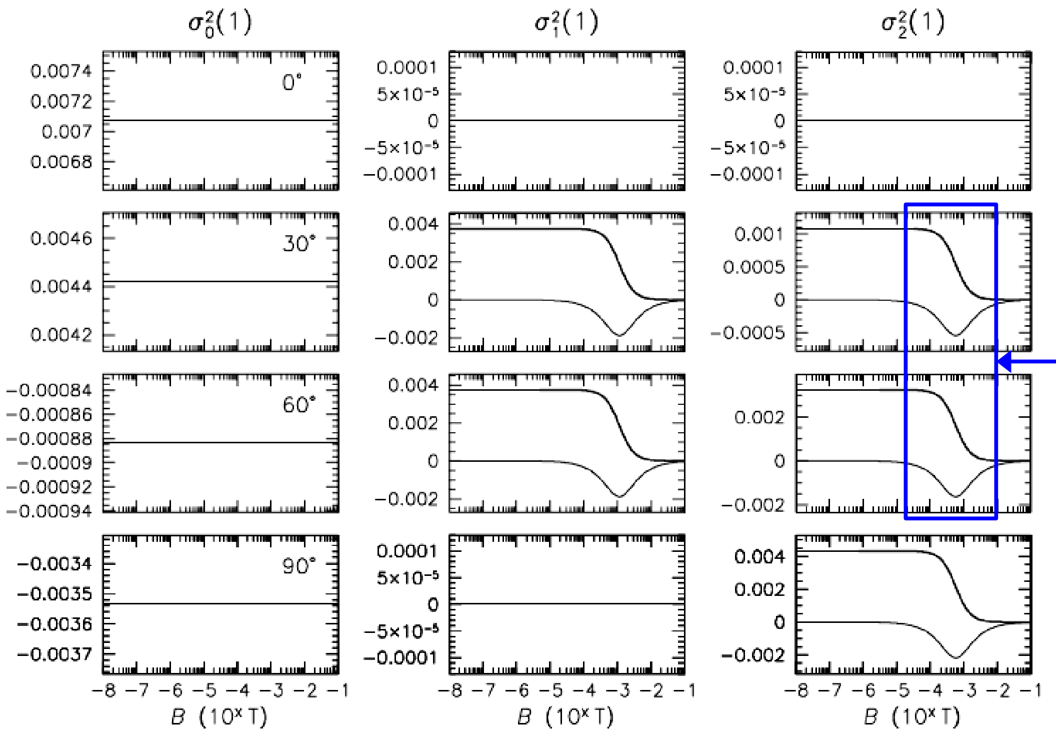


Fig. 12.9. Fractional alignment of the upper level, $J_u = 1$, of the 0–1 atom, as a function of the magnetic field strength, and for various inclinations $(0°, 30°, 60°, 90°)$ of the field with respect to the direction of incident radiation. For this plot, we used $A_{10} = 10^8\,\mathrm{s}^{-1}$ and $w(\omega_{10}) = 10^{-2}$. The thick and thin curves correspond to the real and imaginary parts of σ^2_Q, respectively.

(from Casini & Landi Degl'Innocenti 2008, *Astrophysical Plasmas*, in *Plasma Polarization Spectroscopy*, ed. Fujimoto & Iwamae, Springer)

- atomic coherences correspond to $Q \neq 0$
- $Q = 0$ is not affected by the magnetic field strength (it only depends on the direction of $\boldsymbol{B}$)
- the imaginary parts of the coherences are non zero only when $\omega_B \sim A_{10}$

magnetic regime of the Hanle effect

$$\omega_B \sim A_{10}$$

Zeeman-Effect Diagnostics

Weak-Field Approximation:

$$\xi \equiv (\omega_B / \Delta\omega_T) \ll 1$$

$$I(\omega;\xi) \sim I(\omega;0) + O(\xi^2)$$
$$Q(\omega;\xi) \sim O(\xi^2)$$
$$U(\omega;\xi) \sim O(\xi^2)$$
$$V(\omega;\xi) \sim \xi I'(\omega;0) + O(\xi^3)$$

- $\Delta\omega_T$ is the **Doppler width** at the plasma temperature T
- ξ is a measure of the magnetic strength

- when just a fraction f_B (**filling factor**) of the pixel is "magnetic"

$$I(\omega;\xi) \cong (1-f_B) I(\omega;0) + f_B I(\omega;0) = I(\omega;0)$$
$$V(\omega;\xi) \cong 0(1-f_B) I'(\omega;0) + \xi f_B I'(\omega;0) = (\xi f_B) I'(\omega;0)$$

- (ξf_B) quantifies the **magnetic flux**, not the magnetic strength (since ξ and f_B cannot be disentangled without additional information)

Hanle-Effect Diagnostics

In the **Weak-Field Approximation**:

- $I(\omega;\xi)$ and $V(\omega;\xi)$ behave like in the Zeeman effect
- in contrast (e.g., 90° scattering along $\boldsymbol{B}$; see slide 11)

$$Q(\omega;\xi) \sim p_Q(w;\xi)I(\omega;0) + O(\xi^2)$$

$$U(\omega;\xi) \sim \xi\, p_U(w;\xi)I(\omega;0) + O(\xi^2)$$

where w is the anisotropy of the radiation field

- even if only a fraction f_B of the resolution element is magnetic, ξ and f_B are formally disentangled, hence we can in principle measure the **field strength**!
- because A_{ul} is much smaller than $\Delta\omega_T$, the Hanle effect is typically sensitive to much smaller fields than the Zeeman effect

Zeeman vs Hanle: 180° Ambiguity (1)

- the 180° ambiguity is realized **if and only if** the expressions of the Stokes parameters do not change when

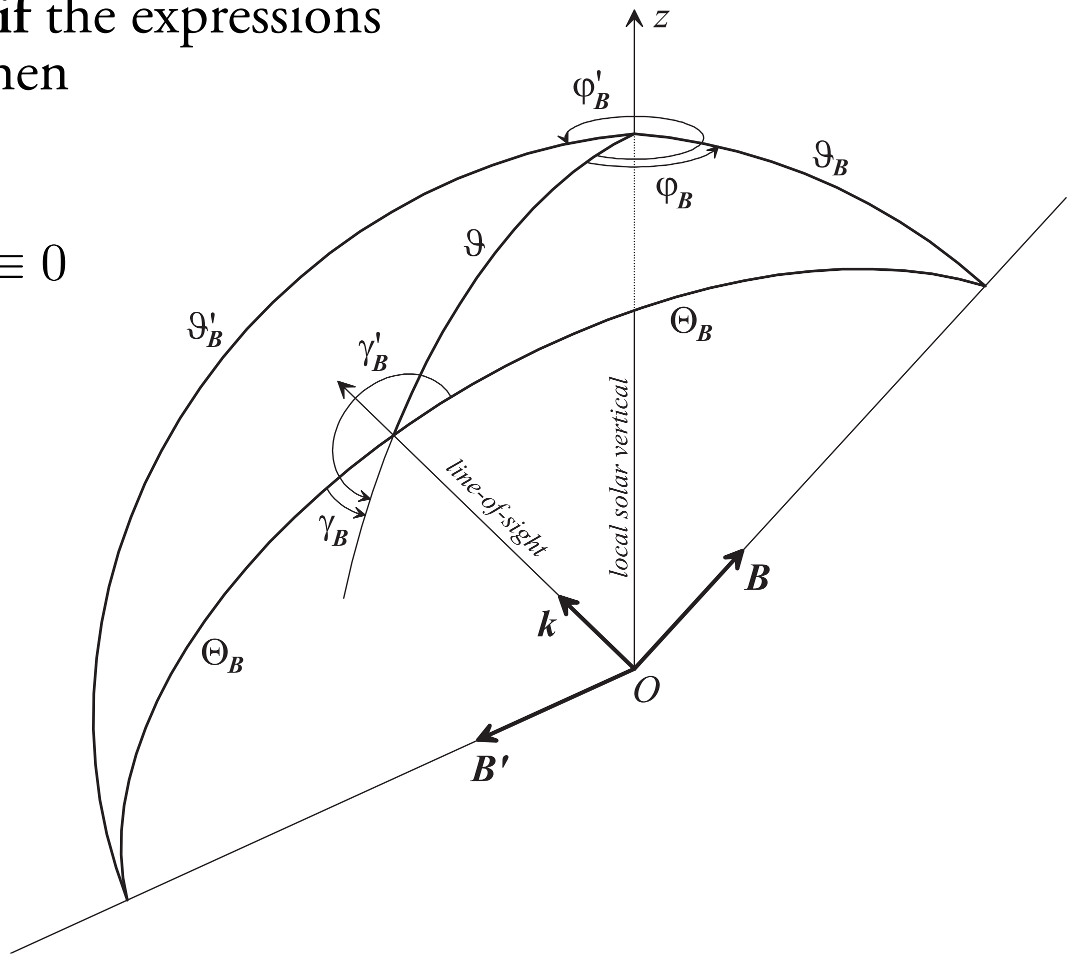
$$\gamma_{\boldsymbol{B}} \to \gamma'_{\boldsymbol{B}} = \pi + \gamma_{\boldsymbol{B}}$$

$$\longrightarrow \quad \Delta\varepsilon_i \equiv \varepsilon_i(\omega, \hat{\boldsymbol{k}}; \gamma_{\boldsymbol{B}}) - \varepsilon_i(\omega, \hat{\boldsymbol{k}}; \gamma'_{\boldsymbol{B}}) \equiv 0$$

- in general, for the Hanle effect we find

$$\Delta\epsilon_i \propto \frac{w}{1+\xi^2} \, \sin\vartheta \cos\vartheta$$

- the 180° ambiguity **only** occurs: 1) in the **absence of radiation anisotropy** ($w = 0$), 2) for observations at the **limb** ($\cos\vartheta = 0$) or at **disk center** ($\sin\vartheta = 0$), or 3) in the **saturated Hanle regime** ($\xi \gg 1$)



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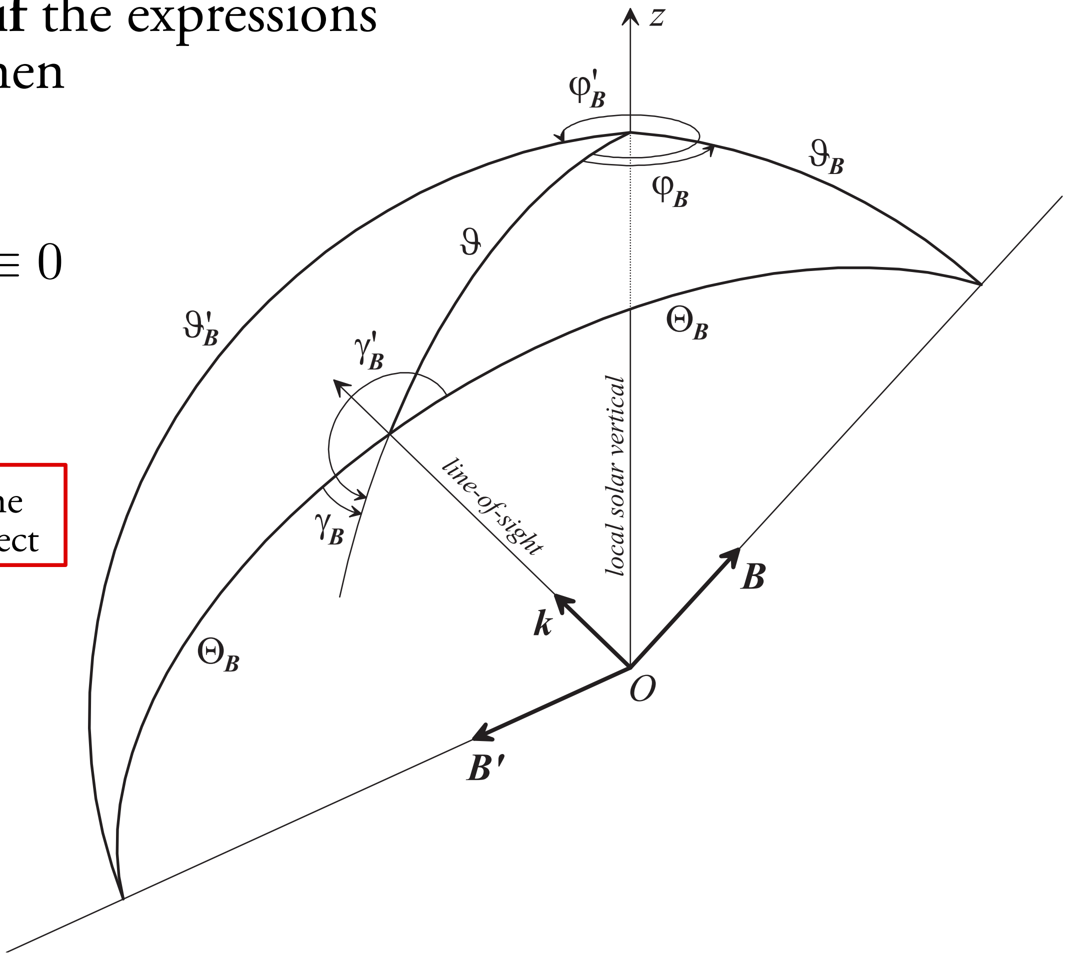
- in general, for the Hanle effect we find

$$\Delta\epsilon_i \propto \frac{w}{1+\xi^2} \sin\vartheta \cos\vartheta$$

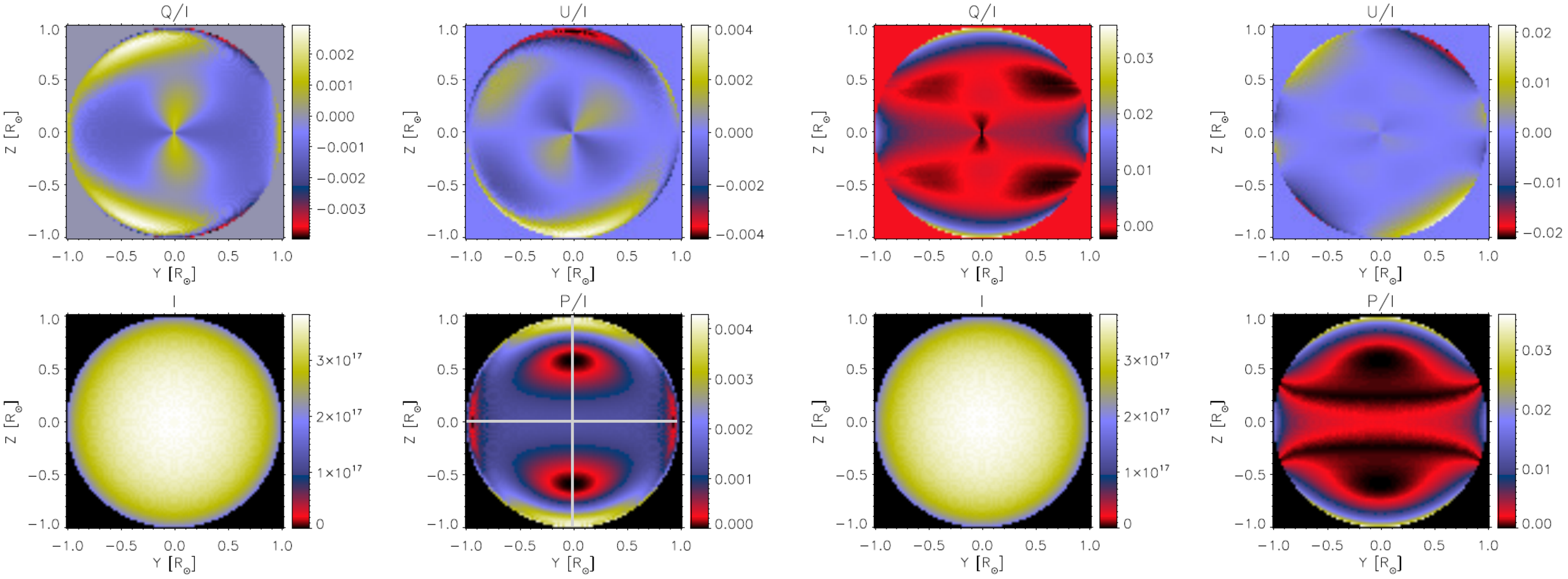
$\to 0$ for the Zeeman effect

- the 180° ambiguity **only** occurs: 1) in the absence of radiation anisotropy ($w = 0$), 2) for observations at the limb ($\cos\vartheta = 0$) or at disk center ($\sin\vartheta = 0$), or 3) in the saturated Hanle regime ($\xi \gg 1$)



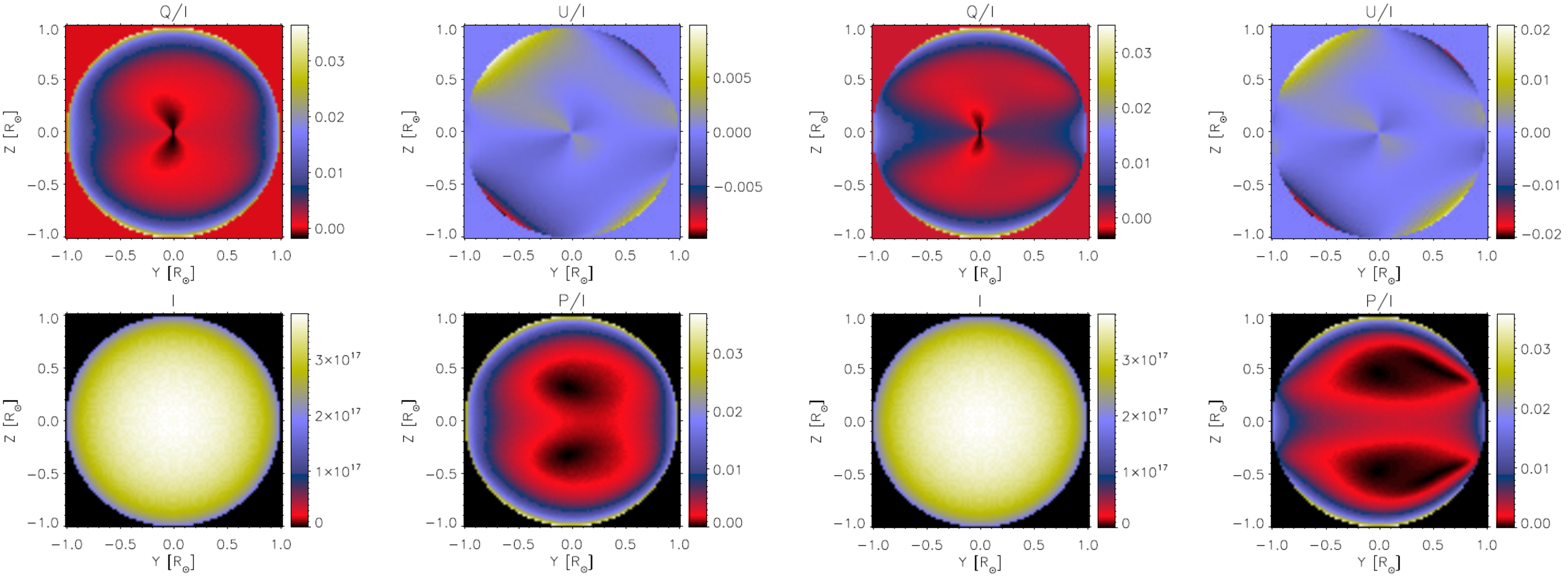
Zeeman vs Hanle: 180° Ambiguity (2)

disk polarization maps of He I 1083 nm in the presence of a **strong** dipole field ($B_{\mathrm{eq}} = 1000$ G), for the Zeeman (left) and Hanle saturated (right) cases; we note the **top-bottom and left-right symmetry** of the P/I maps (the linear-polarization reference is everywhere parallel to the limb)



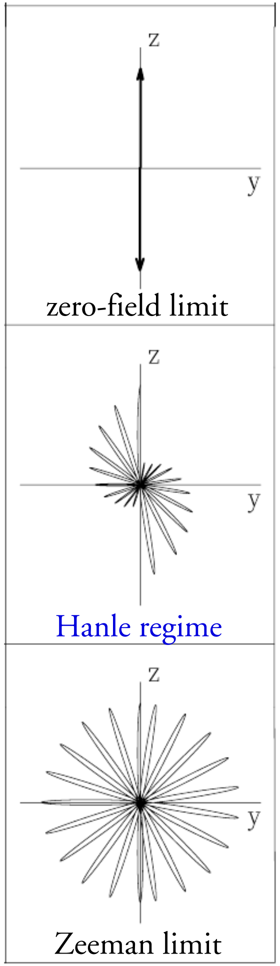
Zeeman vs Hanle: 180° Ambiguity (3)

disk polarization maps of He I 1083 nm in the presence of a **weak** dipolar field ($B_{\rm eq} = 0.1$ G, left; $B_{\rm eq} = 1.0$ G, right), demonstrating the unsaturated Hanle effect; we note how the P/I maps become **left-right asymmetric** because of the **breaking of the 180° ambiguity on disk**



4: *Saturated and Unsaturated Hanle Diagnostics*

Coronal Hanle-Effect Regimes



$\frac{\omega_B}{A} \to 0$

$\frac{\omega_B}{A} \approx 1$

unsaturated Hanle regime

$\frac{\omega_B}{A} \gg 1$

saturated Hanle regime

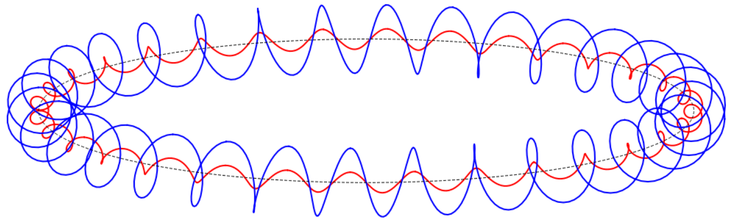
(from Landi Degl'Innocenti & Landolfi 2004)

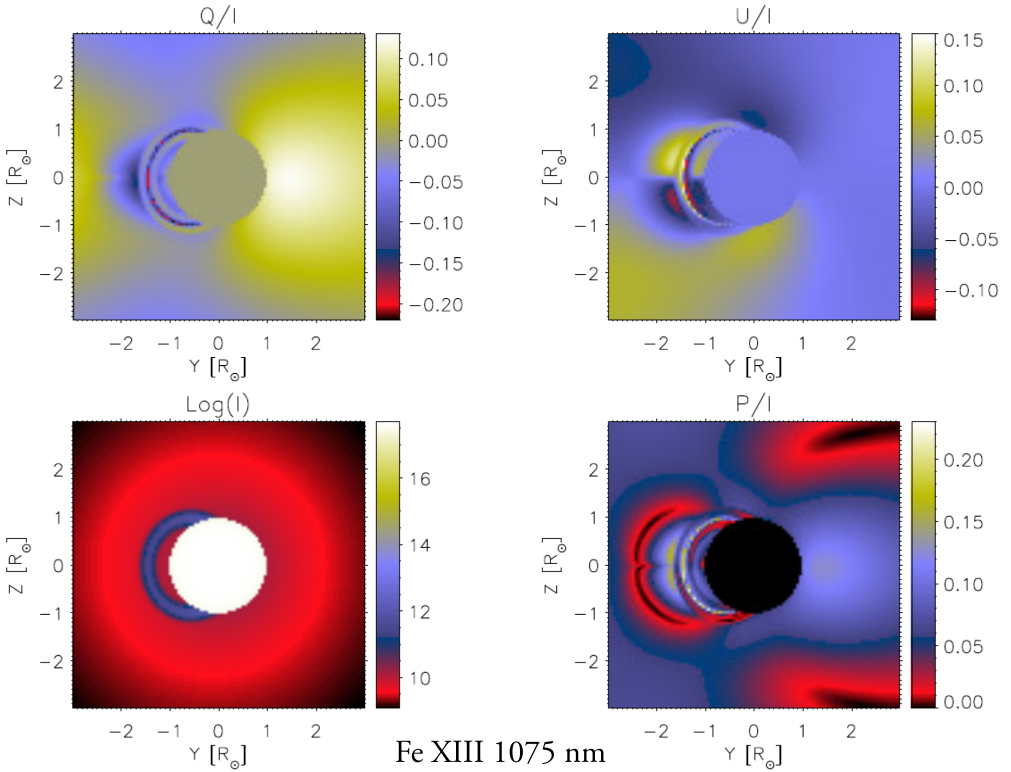
- **field strengths** of relevance for **coronal magnetism** diagnostics span $\sim$3 ROM (say, $\sim$0.1 G to $\sim$100 G)
- transition probabilities of spectral lines observed in the corona span $\sim$7 ROM (say, $\sim 10\ s^{-1}$ to $\sim 10^8\ s^{-1}$)

  $\Rightarrow$ spectral diagnostics exist for both the **unsaturated** and **saturated** Hanle regimes
- strong **EUV/FUV** resonance lines of **electric-dipole** (E1) transitions (e.g., Ne VIII 77 nm, H I 122 nm, C IV 155 nm) are typically in the **unsaturated** regime (e.g., for H I 122 nm, $\omega_B/A \approx 1 \rightarrow B \approx 50$ G)
- **Vis/IR** resonance lines of **magnetic-dipole** (M1) transitions (e.g., Fe XIV 530 nm, Fe XIII 1075/1080 nm) are typically in the **saturated** regime (e.g., for Fe XIII 1075 nm, $\omega_B/A \approx 1 \rightarrow B \approx 5\times10^{-7}$ G)
- for the 2-level atom (J_u, J_l) in the saturated Hanle limit, one can provide simple analytic expressions of the polarized scattering emissivity in the presence of a magnetic field (Casini & Judge 1999)

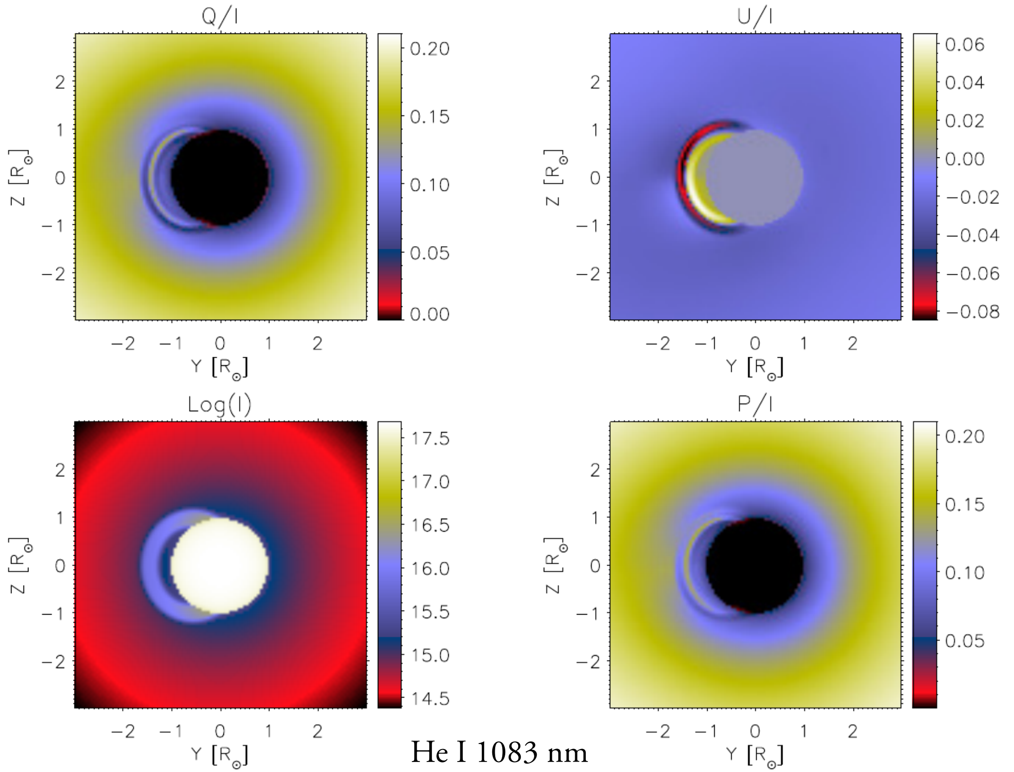
Example: Magnetic Flux Rope (1)

magnetic model includes a family of coiled MFRs with **1.0 G** on-axis field





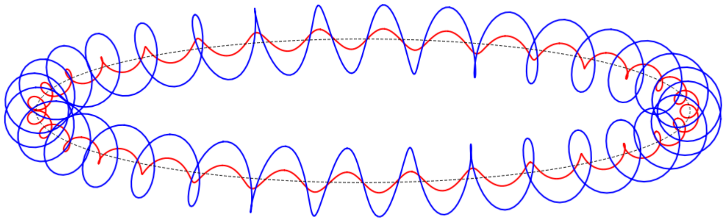
Fe XIII 1075 nm



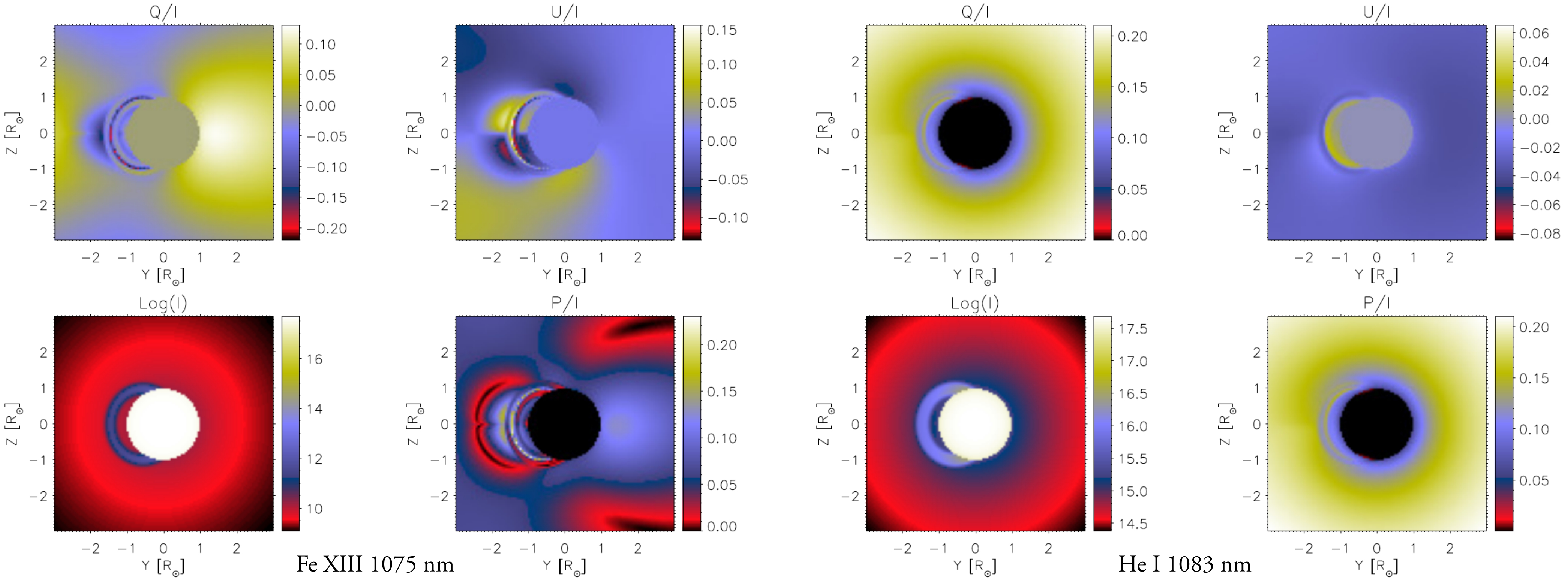
He I 1083 nm

Example: Magnetic Flux Rope (2)

magnetic model includes a family of coiled MFRs with **0.1 G** on-axis field

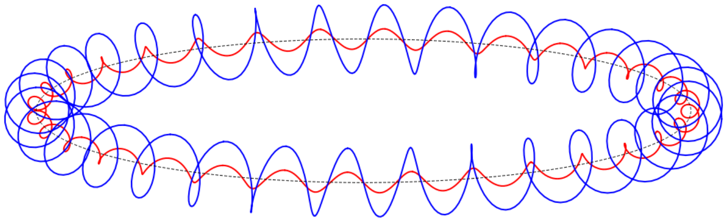


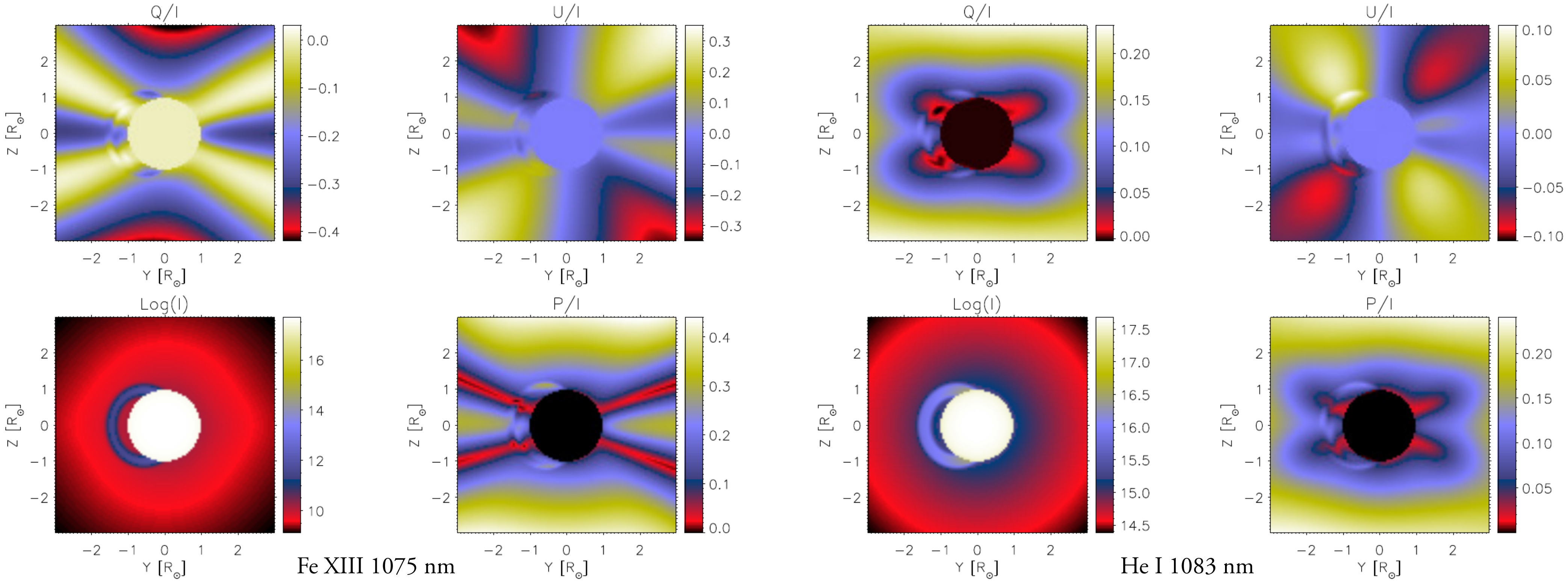
no change to the polarization maps or Hanle-saturated lines



Example: Magnetic Flux Rope (3)

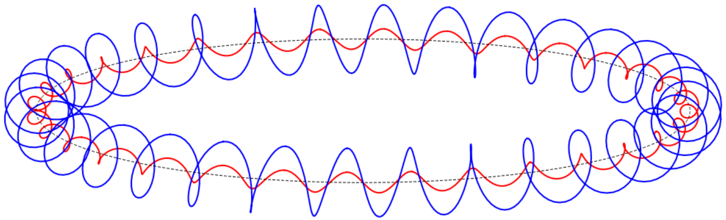
magnetic model includes a family of coiled MFRs with **1.0 G** on-axis field **plus** a global magnetic dipole (B_{eq}=10 G at the surface equator)

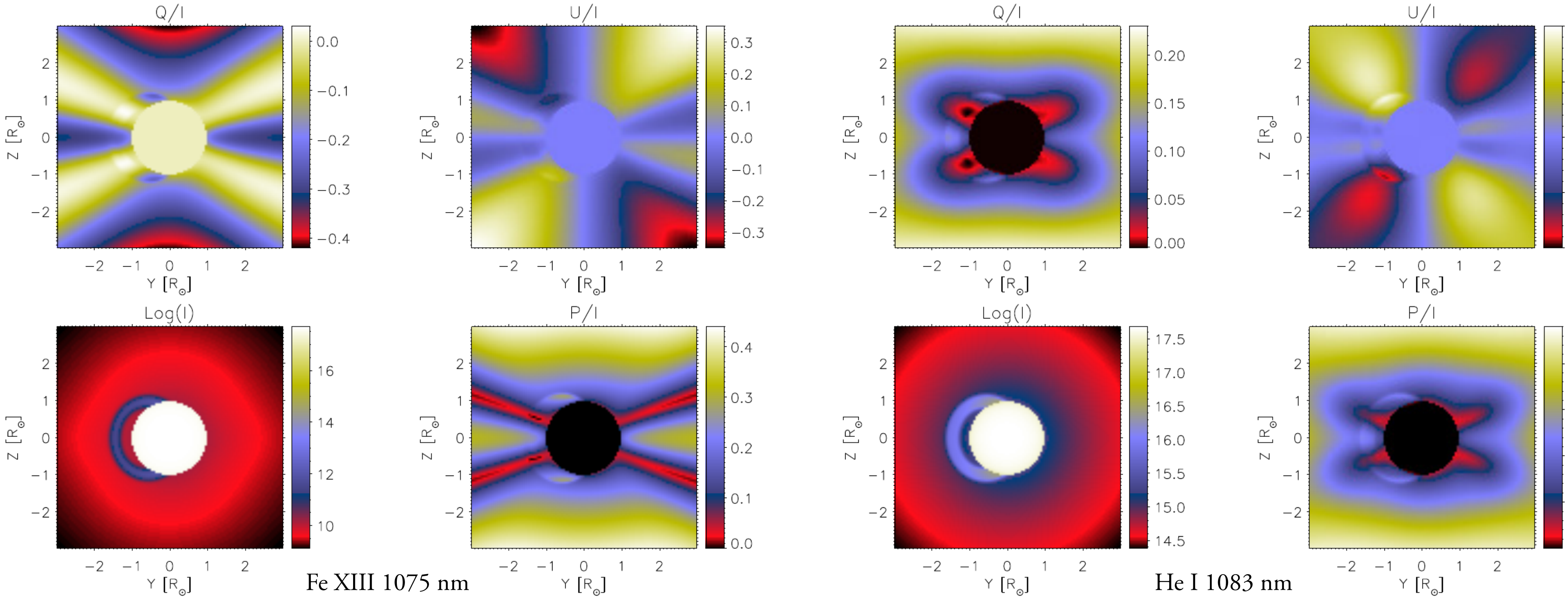




Example: Magnetic Flux Rope (4)

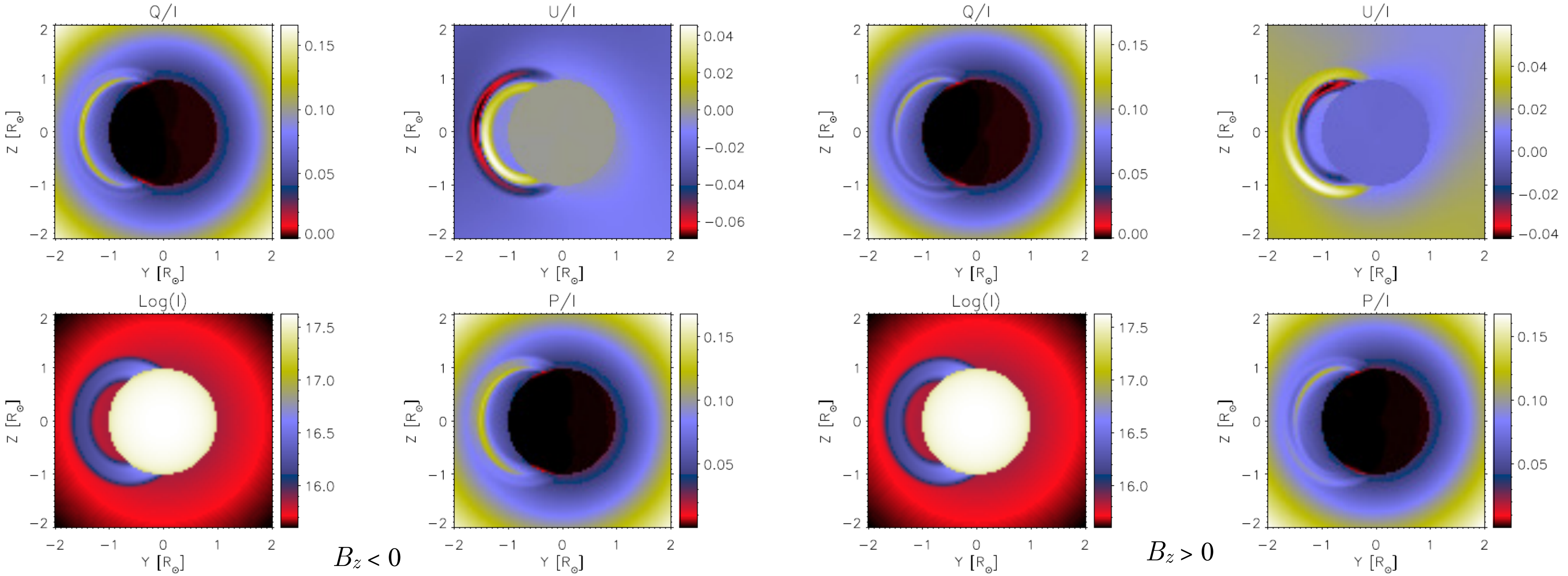
magnetic model includes a family of coiled MFRs with **0.1 G** on-axis field **plus** a global magnetic dipole (B_{eq}=10 G at the surface equator)





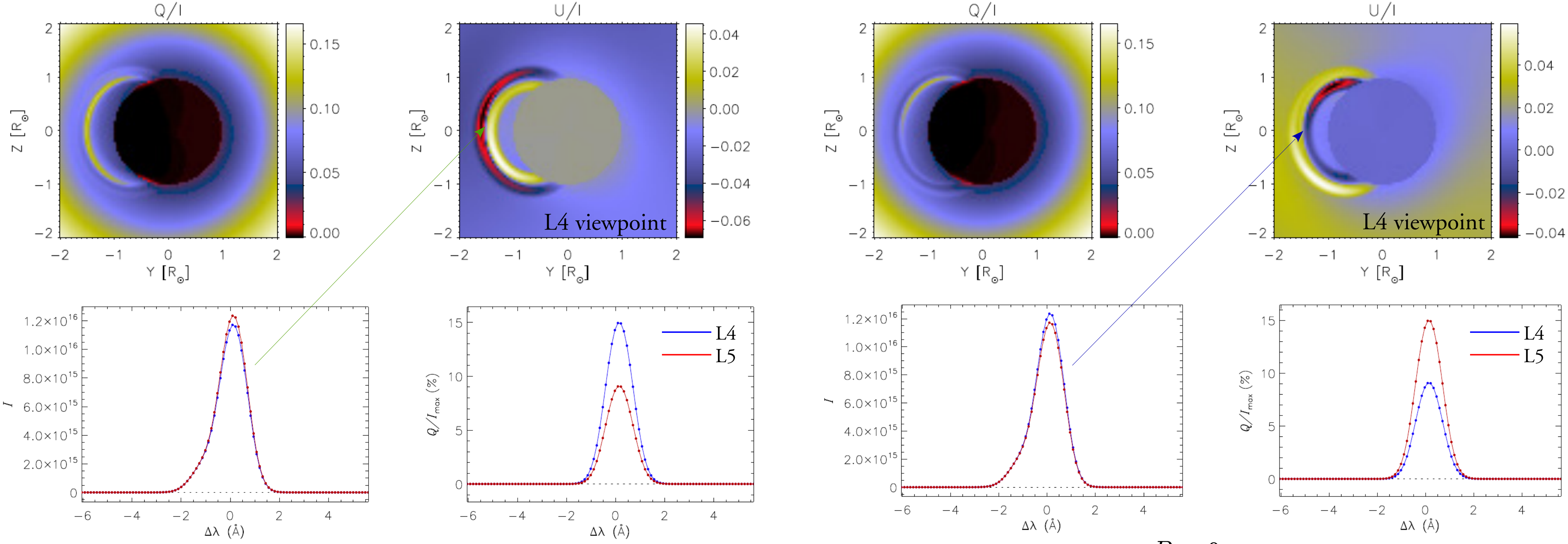
Example: Multi-point Observations (1)

- magnetic model includes a family of coiled MFRs with **1.0 G** on-axis field
- we assume **L4** polarimetric observations in He I 1083 nm of an Earth-directed "CME"
- Hanle-effect polarization enables the discernment of B_z (see also Molnar & Casini 2025)



Example: Multi-point Observations (2)

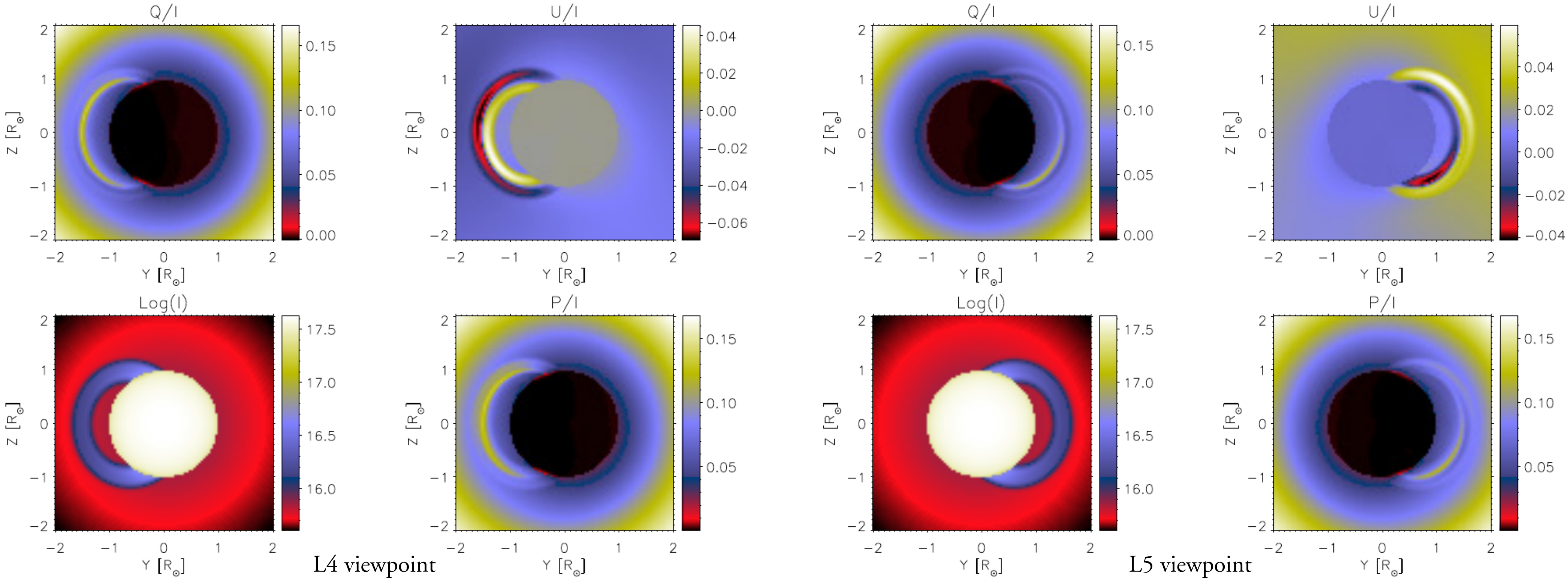
- magnetic model includes a family of coiled MFRs with **1.0 G** on-axis field
- we assume **L4** polarimetric observations in He I 1083 nm of an Earth-directed "CME"
- Stokes profiles at a ***U*-null point on the MFR axis** and on the equatorial plane



$B_z < 0$ $B_z > 0$

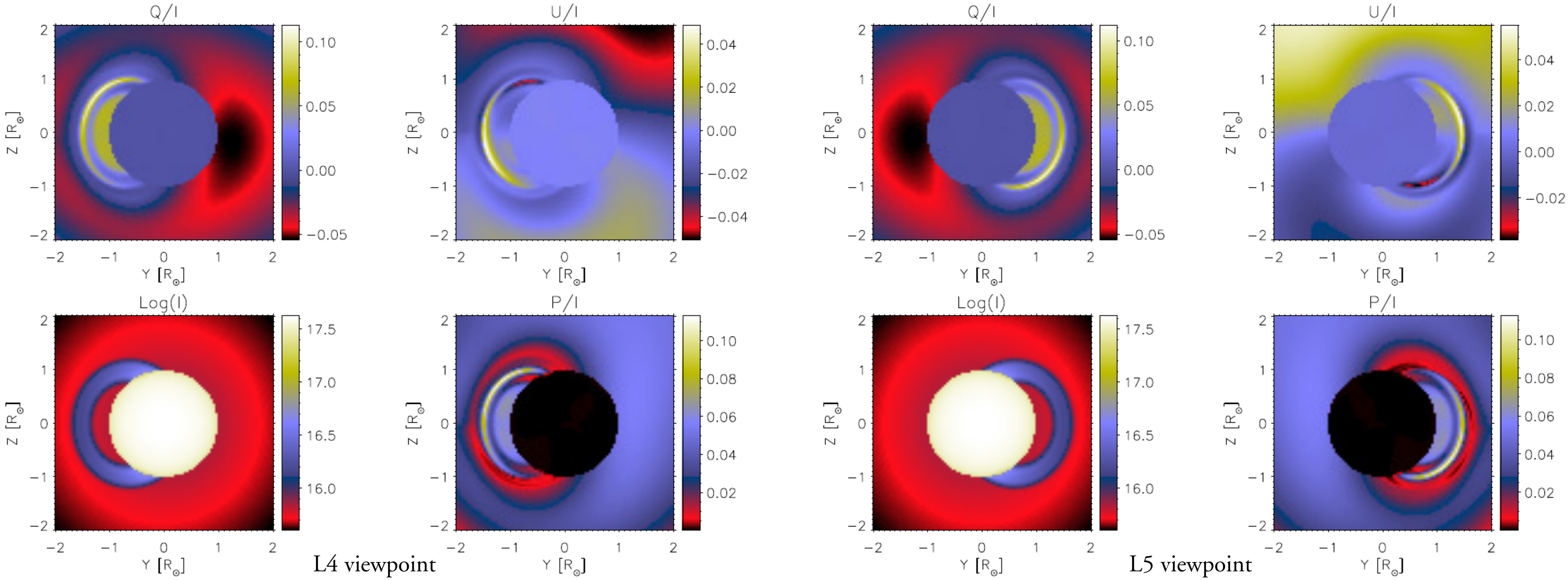
Example: Multi-point Observations (3)

- magnetic model includes a family of coiled MFRs with **1.0 G** on-axis field
- we assume **L4-L5** polarimetric observations in He I 1083 nm of an Earth-directed "CME"
- Hanle-effect polarization maps for the $B_z < 0$ case



Example: Multi-point Observations (4)

- magnetic model includes a family of coiled MFRs with **100 G** on-axis field
- we assume **L4-L5** polarimetric observations in He I 1083 nm of an Earth-directed “CME”
- full saturation of the Hanle effect brings in **Zeeman-like geometric ambiguities**



Conclusions (1)

- light polarization, particularly in spectral lines, is a powerful diagnostic of symmetry breaking processes in stellar atmospheres, such as the presence of magnetic fields (both deterministic and turbulent), of thermal and dynamical gradients in the plasma, and of anisotropic excitation and de-excitation mechanisms of the ions and molecules
- under the ordinary LTE and NLTE conditions of “dense” astrophysical plasmas (e.g., the solar photosphere and lower chromosphere), use of spectro-polarimetry for the diagnosis of magnetic fields is limited to the Zeeman effect, which “generates” spectral line polarization proportionally to the observed magnetic flux
  - a viable diagnostic of magnetic fluxes *strong* enough that the spectral scales of the polarization signal are comparable with the Doppler width of the line
- anisotropic excitation and de-excitation mechanisms produce atomic polarization (population imbalance and quantum coherence among energy levels; NLTE of the 2nd kind), which naturally results in the polarization of the scattered radiation (e.g., the linear polarization of radiation tangent to the limb of a magnetically “quiet” Sun)

Conclusions (2)

- scattering polarization is further modified by the presence of external fields through the Hanle effect, which is produced by the relaxation of quantum coherence with the growing energy separation between atomic levels as a function of the magnetic (electric) *strength*
  - a viable diagnostic of magnetic strengths *weak* enough that the energy splittings are comparable with the natural width of the line
- because ion collisions in a dense plasma lead to the "thermalization" of energy levels, atomic polarization is mainly manifested in tenuous atmospheres (e.g., the solar corona and upper chromosphere), and scattering polarization is a powerful diagnostic of the magnetism of these regions (e.g., Hanle-effect modeling of He I polarization in solar prominences and filaments, and of H Ly_α polarization in the solar corona; "saturated" Hanle effect of M1 coronal emission lines)
- the Hanle effect of He I 1083 nm may be used as a multi-point, linear-polarization diagnostics of the B_z component of a CME-connected MFR, e.g., as observed from the L4-L5 vantage points (see also Molnar & Casini 2025)

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