Magnetic Field Diagnostics with Strong Chromospheric Lines

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Abstract. The complex spectropolarimetric patterns around strong chromospheric lines, the result of subtle spectroscopic and transport mechanisms, are sensitive, sometimes in unexpected ways, to the presence of magnetic fields in the chromosphere, which may be exploited for diagnostics. We apply numerical polarization radiative transfer implementing partially coherent scattering by polarized multi-term atoms, in the presence of arbitrary magnetic fields, in planeparallel stellar atmospheres to study a few important spectroscopic features: Mg ii h-k doublet; Ca ii H-K doublet and IR triplet. We confirm the importance of partial redistribution effects in the formation of the Mg ii h-k doublet in magnetized atmospheres, as previously pointed out for the non-magnetic case. Moreover, we show, numerically and analytically, that a magnetic field produces measurable modifications of the broadband linear polarization even for relatively small field strengths, while circular polarization remains well represented by the magnetograph formula. We note that this phenomenon has already (unknowingly) been observed by UVSP/SMM, and the interest and possibility of its observation in stars other than the Sun. The interplay between partial redistribution in the H-K doublet of Ca ii and metastable level polarization in its IR triplet allow diagnosing the chromospheric magnetic field at different layers and strengths. Our results suggest several new avenues to investigate empirically the magnetism of the solar and stellar chromospheres.

Spectral lines that form in the chromosphere—a rarefied, relatively cool medium—correspond to strong resonant transitions of abundant elements, and are scattered largely unaffected by collisions, which makes that even subtle, fragile radiation-matter interaction processes—partial frequency redistribution (PRD) and coherence between incident and outgoing radiation (Shine et al. 1975), coherence between different atomic levels (Stenflo 1980; Smitha et al. 2011; Belluzzi & Trujillo Bueno 2011), atomic polarization in long-lived metastable levels (Manso Sainz & Trujillo Bueno 2003)—, become observable. Magnetic fields, by removing the degeneracy of the atomic levels and changing the precession axis, disturb the scattering process and the polarization pattern thus betraying their presence, which is important for diagnostic purposes.

A general theory for describing light-matter interaction that accounts for PRD, atomic polarization and coherence in a general multi-term atomic system, in the presence of arbitrary magnetic fields has been recently presented (Casini et al. 2014; Casini & Manso Sainz 2016a,b; Casini et al. 2017). We have developed a numerical polarization radiative transfer code that implements this theory to calculate the emergent Stokes profiles in planeparallel stellar atmospheres (del Pino Alemán et al. 2016). Its application to the formation of the Mg ii h and k doublet in the Sun has already provided a few notable surprises (Figure 1).
Figure 1. The linear polarization pattern (due to scattering) around the $\text{Mg\,\text{II}}$ k-h doublet calculated for a semiempirical solar model atmosphere (FAL-C; Fontenla et al. 1993) is strongly modulated, even far from resonance, in the presence of a magnetic field (here, $B = 100$ G inclined $\theta_B = 30^\circ$ with respect to the vertical and azimuth at $60^\circ$ to the line-of-sight—LOS). The circular polarization is well described by the magnetograph formula. Dotted lines show the reference $B = 0$ case. Yellow, green, cyan, blue, violet, (or light to dark gray) for heliocentric angles $\theta$ with $\mu = \cos \theta = 1$ (disc center), 0.8, 0.5, 0.3, 0.1, respectively.

Rotation (and depolarization) of linear scattering polarization is a characteristic of the Hanle effect (Moruzzi & Strumia 1991). But it is also well-known that the Hanle effect mainly operates in the core spectral lines—here, the polarizable k-line (Stenflo 1994; Landi Degl’Innocenti & Landolfi 2004, hereafter LL04). Why, then, the remarkable rotation of the linear polarization pattern spanning several nm off-resonance in Figure 1? Perhaps even more surprisingly, the reason is magnetooptical (MO) effects (del Pino Alemán et al. 2016, see also Alsina et al. 2016). We have checked this numerically but it is enlightening to integrate the radiative transfer equations for the Stokes parameters (LL04)

$$\frac{d}{ds} \begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix} = - \begin{pmatrix} \eta_I & \eta_Q & \eta_U & \eta_V \\ \eta_Q & \eta_I & -\rho_U & -\rho_V \\ \eta_U & -\rho_V & \eta_I & \rho_Q \\ \eta_V & \rho_U & -\rho_Q & \eta_I \end{pmatrix} \begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix} + \begin{pmatrix} \epsilon_I \\ \epsilon_Q \\ \epsilon_U \\ \epsilon_V \end{pmatrix}$$
for a constant properties slab of total of optical thickness \( \tau = \eta L \) (L the geometrical thickness), where \( \eta \) is the absorption coefficient, \( \eta_{Q,U,V} \) the dichroism coefficients, \( \rho_{Q,U,V} \) the MO coefficients, and \( \epsilon_{Q,U,V} \) the emissivities.

For unpolarized lower levels, the \( \rho \) and \( \eta \) coefficients depend on the magnetic field through the Zeeman splitting of the line profiles. Let \( \Delta \) be the Zeeman splitting normalized to the line width. In the weak field limit, \( \rho_v \) and \( \eta_v \sim \Delta \), while \( \eta_{Q,U,V}, \rho_{Q,U} \sim \Delta^2 \) (LL04). We shall assume \( \rho_v \gg \eta_v, \rho_Q, \rho_U \) and proceed perturbatively. We will further assume \( \rho_v \gg \eta_v \) in the line wings. Then, the emergent radiation assuming unpolarized illumination \( (I_0) \) is

\[
I = I_0 e^{-\tau} + \frac{\epsilon_I}{\eta_I} (1 - e^{-\tau}) + \ldots \\
Q = \frac{1 - (c - \rho s) e^{-\tau}}{1 + \rho^2} \frac{\epsilon_Q}{\eta_I} + \frac{\rho - (\rho c + s) e^{-\tau}}{1 + \rho^2} e_U + \ldots \tag{1a}
\]

\[
U = \frac{\rho - (\rho c + s) e^{-\tau}}{1 + \rho^2} \frac{\epsilon_U}{\eta_I} + 1 - (c - \rho s) e^{-\tau} \frac{\epsilon_U}{1 + \rho^2} + \ldots \tag{1b}
\]

where the dots stand for higher order terms including dichroism, \( \rho = \rho_v/\eta_I, c = \cos(\tau \rho), \) and \( s = \sin(\tau \rho) \). In the optically thin limit \( (\tau \ll 1) \),

\[
I = I_0 + \tau \left( \frac{\epsilon_I}{\eta_I} - I_0 \right), \quad Q = \tau \frac{\epsilon_Q}{\eta_I} - \tau^2 \frac{\rho \rho_v e_U}{\eta_I \eta_I}, \quad U = \tau \frac{\epsilon_U}{\eta_I} + \tau^2 \frac{\rho \rho_v e_Q}{\eta_I \eta_I}; \tag{2}
\]

in the optically thick limit \( (\tau \gg 1) \),

\[
I = \frac{\epsilon_I}{\eta_I}, \quad Q = \frac{1}{1 + \rho^2} \frac{\epsilon_Q}{\eta_I} - \frac{\rho \epsilon_U}{1 + \rho^2 \eta_I}, \quad U = \frac{\rho \epsilon_Q}{1 + \rho^2 \eta_I} + \frac{1}{1 + \rho^2 \eta_I} \frac{\epsilon_U}{\eta_I}; \tag{3}
\]

In LTE, the case in classical Zeeman diagnostics, the hierarchy above on dichroism and MO coefficients also implies that \( \epsilon_v \gg \epsilon_Q, \epsilon_U \), and then, MO terms in (1) become of higher order to the (ellipsis) dichroism terms, which are governed by the (zeroth order) intensity. Thus, MO are second order in the optical depth (Equation [2]), and high
order on the Zeeman splitting ($\rho V \times \epsilon_{Q,U} \sim \Delta \times \Delta^2$). For those reasons, the fundamental importance of MO effects was firstly understood from their characteristic signature in the core of spectral lines, in spectropolarimetric observations of sunspots (Wittmann 1971; Landi Degl’Innocenti 1979; Landolfi & Landi Degl’Innocenti 1982; Skumanich & Lites 1987).

Scattering polarization, however, is a zeroth order effect ($\epsilon_{Q,U} \sim \Delta^0$) and MO effects appear at lowest order on the perturbative analysis (Equations [1]). Moreover, it is well known that interference between $J$-levels of the same term and PRD greatly enhance the scattering polarization patterns around strong resonance lines (Stenflo 1980; Auer et al. 1980; Stenflo 1996; Belluzzi & Trujillo Bueno 2011; Smitha et al. 2011; Belluzzi & Trujillo Bueno 2012, LL04). Surprisingly, only very recently has the role of MO effects described here been recognized in the magnetical modulation the linear polarization patterns around strong resonance lines (del Pino Alemán et al. 2016; Alsina Ballester et al. 2016).

MO rotation in the wings is a transport phenomenon different from the Hanle effect taking place in the core of the k-line (see Figure 2). In the wings, we may neglect the variation of $\epsilon_{Q,U}$ with the magnetic field. Then, from equations (3),

$$\frac{Q}{I} = \frac{1}{1 + \rho^2} \left( \frac{Q}{I} \right)_0, \quad \frac{U}{I} = \frac{\rho}{1 + \rho^2} \left( \frac{Q}{I} \right)_0, \tag{4}$$

where the 0 subindex refers to the non magnetic case. As $\rho$ varies (with field strength or geometry), equations (4) describe an arc of a circle centered at $((Q/I)_0,(U/I)_0)$ in the $Q-U$ plane (cf. panels a, c, and d in Figure 2).
Figure 4. Broadband (passband $\Delta$) linear polarization is strongly modulated by the magnetic field geometry. Each curve corresponds to a fixed magnetic field inclination ($\theta_B = 30^\circ$), strength (solid lines: 20 G; dotted lines: 100 G), LOS ($\mu = 0.1$), and azimuth $0 \leq \varphi_B < 2\pi$. Larger polarization values are obtained with $\Delta = 4$ nm which captures the polarization maxima on the wings at $\sim 1$ nm off-resonance (cf Figure 1). Cancellation due to the negative polarization branch between the $H$ and $K$ lines is more noticeable with smaller $\Delta$.

Spectropolarimetric observations of linear polarization in the MgII h-k lines close to the solar limb were obtained by Henze & Stenflo (1987; see Figure 3) using the Ultraviolet Spectrometer and Polarimeter (UVSP; Woodgate et al. 1980) onboard the Solar Maximum Mission (SMM; see Strong et al. 1999). They confirmed the presence of strong polarization parallel to the limb in the wings of the lines (blue of the k-line, red of the h-line) due to scattering, but the existence of a negative (radial) polarization branch between the lines remained uncertain. We have reanalysed the data applying an on-flight correction similar to the procedure of Giono et al. (2017). Observations at disk center with low spatio-temporal resolution are expected to be unpolarized due to symmetry reasons. However, the spatially and spectrally averaged UVSP/SMM observations at disk center show a residual $Q/I$ offset $\sim 0.5\%$. When this spurious signal is removed from all the data (Figure 3), the corrected data nicely fall between the 0 G profile and the $Q/I = 0$ axis and in particular, the negative branch is confirmed. In fact, according to the MO theory explained here, the data points should not fall along the pure scattering profile ($B = 0$ G line in Figure 3) but rather fluctuate due to different magnetic field configurations likely present in the observed areas. The variability in the observations is therefore not (only) due to noise, but due to actual fluctuations of the solar magnetic field. A reanalysis of that data set, including the observed (unpublished) $U/I$ pattern, would be of great interest.

The large polarization on the wide extended wings and their sensitivity to the magnetic field (del Pino Alemán et al. 2016) suggests the prospect of broadband polarimetry (BBP). Interestingly, contrary to what is often the rule in polarimetry, the larger the passband, the largest the signal (Figure 4). That is because the negative branch (which leads to cancellations) and the lower polarization close to the lines are more than compensated by the strong polarization $\sim 1$ nm away from the lines. This comes at the price; the wings form deeper in the atmosphere than the high chromosphere probed by
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the core of the h and k lines. In numerical experiments we find that if the atmosphere is unmagnetized below 1 Mm then the MO modulation occurs only in the close neighborhood of the lines, the pattern away and between them remains unaffected. Yet, we can think of at least two interesting applications for BBP. It offers the possibility of polarimetric imaging of the magnetic field in the lower chromosphere and photosphere, for example, from context or slit-jaw images which would constrain and facilitate the interpretation of spectropolarimetric observations. Then, study of stellar magnetic fields (and rotation) would greatly benefit from BBP at this wavelengths.

Figure 5. The grand linear polarization pattern of the Ca ii H-K doublet (upper panel) is largely due to scattering and PRD effects; the scattering polarization signal in the 866.2 and 854.2 nm lines of the IR triplet (lower panels) is fundamentally due to differential polarization absorption (dichroism) by the aligned metastable \( ^2D_{3/2,5/2} \) levels. The Ca ii H-K lines and the IR triplet share the same upper term \(^2P\). Hence, PRD and atomic polarization have been simultaneously considered for a consistent description of scattering polarization in such \( \Lambda \)-type atom. \( Q/I \) calculated in a FAL-C solar model atmosphere at different heliocentric angles (\( \mu = 0.1, 0.3, 0.5, 0.8 \), for violet, cyan, green, yellow—or dark to light gray—lines, respectively).

In alkaline earth ions heavier than Mg, the first excited shell above the ground s level is not a \( p \) but a \( d \) electronic shell. Consequently, the lowest (five) energy levels become a \( \Lambda \)-type system—a doublet analogous to the Mg ii h and k lines, and a triplet between the doublets upper levels and the metastable \( D \) term. Notably, in the case of Ca ii, both the H and K doublet and the IR triplet form in the chromosphere, and both
show remarkable scattering polarization patterns; the former dominated by PRD and level interference (Stenflo 1980), the latter by dichroism from lower-level atomic polarization (Manso Sainz & Trujillo Bueno 2003). A consistent treatment of the relevant processes in this multilevel system is done for the first time in Figure 5. The role of the magnetic field coupling doublet and triplet systems cannot be discussed in this short note.

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