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Atomic Scattering Polarization. Observations, Modeling, Predictions

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Abstract. This paper highlights very recent advances concerning the identification of new mechanisms that introduce polarization in spectral lines, which turn out to be key for understanding some of the most enigmatic scattering polarization signals of the solar visible spectrum. We also show a radiative transfer prediction on the scattering polarization pattern across the Mg II h & k lines, whose radiation can only be observed from space.

Keywords. Polarization, radiative transfer, magnetic fields, Sun: atmosphere, stars: atmosphere

1. Introduction

A key goal in astrophysics is to investigate the magnetism of the atmospheres of the Sun and of other stars through the measurement and interpretation of polarization in spectral lines. The first step is always to decipher and understand the physical origin of the observed spectral line polarization. The second is to develop suitable techniques for modeling the spectropolarimetric observations, in order to infer the magnetic field vector. In general, to reach these goals we need to solve the complex (non-local and non-linear) problem of the generation and transfer of polarized radiation in a highly inhomogeneous and dynamic medium (e.g., the solar atmosphere). The same techniques are useful to make theoretical predictions in unexplored spectral ranges (e.g., in the vacuum UV).

The polarization of solar spectral lines is caused by the joint action of anisotropic radiation pumping (which produces atomic level polarization -that is, population imbalances and quantum interference between the level's sublevels) and the Hanle and Zeeman effects. This paper deals with a few selected examples of the spectral line polarization produced by the absorption and scattering of anisotropic radiation by atoms (atomic scattering polarization). The main aim is to highlight some interesting, recently-discovered physical mechanisms that are key for understanding the curious fractional linear polarization signals observed in the IR triplet of O I (Del Pino Alemán *et al.* 2015) and in the D_1 lines of Ba II and Na I (Belluzzi & Trujillo Bueno 2013). The paper finishes with a theoretical prediction concerning two UV spectral lines, namely the Mg II h & k lines.

2. The approach

The essential link between theory and spectro-polarimetric observations is radiative transfer modeling of the intensity and polarization of the emergent spectral line radiation. We formulate the problem's equations (i.e., the statistical equilibrium and radiative

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transfer equations) within the framework of the following theories for the generation and transfer of polarized radiation.

2.1. *The density matrix theory for completely uncorrelated scattering*

This theory is explained in great detail in the monograph by Landi Degl'Innocenti & Landolfi (2004). Within the framework of this theory the scattering line polarization phenomenon is described as the temporal succession of 1st-order absorption and re-emission processes, considered as statistically independent events. For the important case of a multilevel atom neglecting quantum interference between the substates pertaining to different levels this theory is a reliable approach whenever the radiation field that pumps the atomic system is flat over a frequency interval larger than the width of the atomic levels. The theory is suitable for modeling many diagnostically important spectral lines, such as the He I 10830 Å and D_3 multiplets (e.g., Trujillo Bueno *et al.* 2002a; Casini *et al.* 2003), the Sr I 4607 Å line (e.g., Trujillo Bueno & Shchukina 2007), the IR triplet of Ca II (e.g., Manso Sainz & Trujillo Bueno 2003a), or the O I IR triplet considered in the next section.

Within the framework of the density matrix theory for completely uncorrelated scattering the solution of the statistical equilibrium equations for the multipolar components of the atomic density matrix determines the excitation state of the atomic system, from which the emergent Stokes profiles can then be calculated by solving the radiative transfer equations. Accurate and efficient numerical methods and radiative transfer codes have been developed for solving this so-called non-LTE problem of the 2nd kind (Trujillo Bueno 1999, 2003; Manso Sainz & Trujillo Bueno 2003b; Štěpán & Trujillo Bueno 2013; Del Pino Alemán *et al.* 2015).

One of the attractive features of this theory for the generation and transfer of polarized radiation is that it allows us to consider realistic multilevel atoms, taking fully into account the circulation of atomic polarization between the atomic levels and the impact, on the scattering line polarization, of the presence of atomic polarization in the line's upper and lower levels. This is important because, in general, there are two mechanisms that contribute to the "scattering polarization" observed in a spectral line:

- Selective emission of polarization components, due to the atomic polarization of the upper level of the line transition.
- Selective absorption of polarization components, due to the atomic polarization of the lower level of the line transition.

This can be easily understood by considering the case of an unmagnetized and one-dimensional (1D) model atmosphere. The ensuing transfer equations for the Stokes parameter Q reads:

$$\frac{d}{ds}Q = [\epsilon_Q \; - \; \eta_Q I] \; - \; \eta_I Q, \tag{2.1}$$

with

$$\epsilon_Q = \epsilon_0 \phi_\nu \frac{3}{2\sqrt{2}}(1-\mu^2)\mathcal{W}\rho^2_0(u), \tag{2.2}$$

$$\eta_Q = \eta_0 \phi_\nu \frac{3}{2\sqrt{2}}(1-\mu^2)\mathcal{Z}\rho^2_0(l), \tag{2.3}$$

where ϵ_0 and η_0 are proportional to the number density of the atoms under consideration, $\rho^2_0(i)$ is the atomic alignment that quantifies the population imbalances between the line's level i sublevels, either the upper ($i = u$) or the lower ($i = l$) one, ϕ_ν is the line's absorption profile, $\mu = \cos\theta$ (with θ the angle between the local vertical and the direction of the considered radiation beam), while $\mathcal{W}$ and $\mathcal{Z}$ are coefficients that depend on the angular momentum values of the line's upper and lower levels. Therefore, Stokes Q can be produced either because the emission coefficient $\epsilon_Q \neq 0$ (selective emission of polarization components) and/or because the absorption coefficient $\eta_Q \neq 0$ (selective absorption of polarization components). This last contribution is termed "zero-field" dichroism, because it has nothing to do with the Zeeman effect (cf., Trujillo Bueno & Landi Degl'Innocenti 1997; Manso Sainz & Trujillo Bueno 2003a).

Since the transfer equation for Stokes I is

$$\frac{d}{ds} I = [\epsilon_I - \eta_Q Q] - \eta_I I \approx \epsilon_I - \eta_I I, \tag{2.4}$$

with $\epsilon_I \approx \epsilon_0 \phi_\nu \rho^0_0(u)$ and $\eta_I \approx \eta_0 \phi_\nu \rho^0_0(l)$ (with $\rho^0_0(i)$ proportional to the overall population of level i), it is easy to show that at the height in the model atmosphere where the line-center optical depth is unity along the line of sight

$$\frac{\eta_Q I}{\epsilon_Q} \approx \frac{\mathcal{Z}}{\mathcal{W}} \frac{\sigma^2_0(l)}{\sigma^2_0(u)}, \tag{2.5}$$

where $\sigma^2_0(i) = \rho^2_0(i)/\rho^0_0(i)$ is the fractional atomic alignment of level i. These $\sigma^2_0(i)$ values at each spatial point of the model atmosphere under consideration have to be calculated by solving the statistical equilibrium equations for the elements of the atomic density matrix (see Chapter 7 of Landi Degl'Innocenti & Landolfi 2004). The particular case of a two-level atomic model is very useful, because it allows us to show that

$$\sigma^2_0(u) \approx \frac{-1}{2(1+\delta_u)} [\frac{J^2_0}{J^0_0} + \sigma^2_0(l)], \tag{2.6}$$

$$\sigma^2_0(l) \approx \frac{1}{2(1+\delta_l)} [\frac{J^2_0}{J^0_0} - \sigma^2_0(u)], \tag{2.7}$$

where J^2_0/J^0_0 is the fractional anisotropy of the incident spectral line radiation, while $\delta_u = D^{(2)}_u/A_{ul}$ and $\delta_l = D^{(2)}_l/B_{lu} J^0_0$ are, respectively for the upper and lower level, the rate of elastic collisions with neutral hydrogen atoms multiplied by the level's radiative lifetime. For ground and metastable levels $A_{ul} \gg B_{lu} J^0_0$; therefore, in sufficiently deep regions of the solar atmosphere δ_l can be much larger than δ_u and $\sigma^2_0(l) \to 0$.

2.2. *The metalevels density matrix theory for completely correlated scattering*

In reality, the phenomenon of scattering polarization in a spectral line is intrinsically a 2nd-order process, where frequency correlations between the incoming and outgoing photons can occur. A convenient theory to treat the limit of completely correlated (or coherent) scattering in the atomic rest frame was proposed by Landi Degl'Innocenti *et al.* (1997), based on the semi-classical picture of metalevels (i.e., each level is viewed as a continuous distribution of sublevels). In the coherent scattering limit elastic collisions do not cause a transition to a sublevel different to the one the atom was excited, so the atom de-excites from the same sublevel where the previous transition ended. Belluzzi *et al.* (2013) have extended the theory by including the possibility of excitations and de-excitations caused by inelastic collisions with electrons, in addition to the radiative transitions.

There are several diagnostically important resonance lines which result from transitions between a ground term, composed of the ground level $^2S_{1/2}$, and the first excited term, composed of the $^2P_{1/2}$ and $^2P_{3/2}$ levels. Examples are the Na I D_2 (5890 Å) and D_1 (5896

Å) lines (whose line-core radiation originates in the lower chromosphere) and the Mg II h & k lines around 2800 Å (whose line-core radiation encodes information on the upper chromosphere, just below the chromosphere-corona transition region). A two-term atomic model with unpolarized and infinitely sharp lower level is suitable for investigating the scattering polarization in these resonance lines, in as far as the assumption that there is no atomic polarization in the lower level is suitable. This is not necessarily the case for the ground level of Na I, because 100% of sodium has hyperfine structure due to its nuclear spin $I = 3/2$ (Landi Degl'Innocenti 1998; Trujillo Bueno *et al.* 2002b). However, as clarified in these papers, if ground-level polarization is required for producing the enigmatic scattering polarization observed in the sodium D_1 line then the magnetization of the lower solar chromosphere should be very weak, with $B<1$ Gauss. Therefore, it is important to clarify if we can have significant scattering polarization in the Na I D_1 line without the need of ground-level polarization (see Section 4).

A heuristic way to describe the transfer of resonance line polarization with partial frequency redistribution and J-state interference with such two-term atomic model is by introducing a total redistribution matrix defined as the linear combination of a $R_{\rm II}$ matrix, which describes the above-mentioned limit of completely correlated (or coherent) scattering in the atomic rest frame, and a $R_{\rm III}$ matrix, which describes the limit of completely uncorrelated scattering (complete frequency redistribution, CRD) in the atomic rest frame. Starting from the expression obtained by Landi Degl'Innocenti *et al.* (1997) in the atomic rest frame, Belluzzi & Trujillo Bueno (2012; 2014) have derived the laboratory frame expression of $R_{\rm II}$, which allows to take into account the effect of Doppler redistribution assuming Maxwellian velocity distributions. Belluzzi & Trujillo Bueno (2014) have also proposed an expression for $R_{\rm III}$ for estimating its impact on the wings of the line. Moreover, they have shown that the same approach can be applied to describe the case of a two-level atom with HFS. Recently, Belluzzi *et al.* (2015a; 2015b) have extended the theory to treat the more complicated case of a two-term atom taking into account the HFS of all the J-levels and the possibility of quantum interference even between the F-levels pertaining to the two different upper J-levels.

3. Chromospheric dichroism in photospheric lines

Figure 1 shows spectropolarimetric observations of the quiet Sun disk, at three distances from the nearest limb, taken in the IR triplet of O I. The curious point here is that while the lines at 7772 Å (hereafter, line 1) and 7774 Å (hereafter, line 2) showed positive Q/I signals, the opposite sign was found for the 7775 Å line (hereafter, line 3).

These O I spectral lines have the same (metastable) lower level, whose angular momentum is $J_l = 2$; the angular momentum values of the three upper levels of increasing energy are 1, 2 and 3. Therefore, in principle, all these levels can carry atomic alignment and contribute to the observed scattering polarization. When observed on the solar disk, the line-center of their Stokes $I(\lambda)$ profiles originates in the photosphere, around 250 km above the visible solar surface for a line of sight with $\mu = \cos\theta = 0.1$ (θ being the heliocentric angle). At such low photospheric heights the number density of neutral hydrogen atoms is of the order of $10^{16}\,{\rm cm}^{-3}$, so we may wonder if elastic collisions between O I and neutral hydrogen atoms are able to completely depolarize such levels.

Figure 2 shows the variation with height in a semi-empirical model of the quiet solar atmosphere of the rates of such elastic collisions, both for the lower ($D_l^{(2)}$) and upper ($D_u^{(2)}$) levels of the three lines. Clearly, these collisional rates decrease with height in the solar model atmosphere because they are proportional to the hydrogen number density,

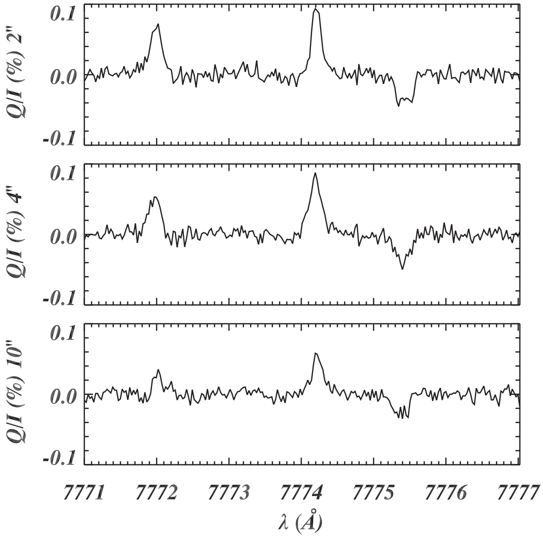

Figure 1. THÉMIS observations of the scattering polarization in the IR triplet of O I at the three indicated on-disk positions from the nearest limb. The positive reference direction for Stokes Q is the parallel to the nearest limb. From Trujillo Bueno *et al.* (2001).

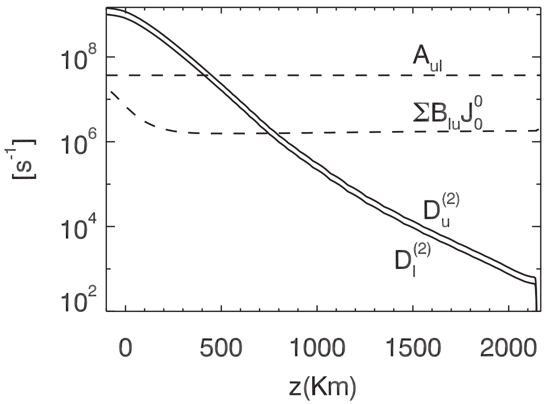

Figure 2. The variation with height in a semi-empirical model of the quiet solar atmosphere of the rates of elastic collisions with neutral hydrogen atoms, for the levels of the O I IR triplet (solid curves). The upper and lower dashed curves indicate the height variation of the rates of spontaneous radiative emissions and of radiative absorptions, respectively. From Del Pino Alemán *et al.* (2015).

which decreases exponentially with height. The rates of elastic collisions have to be compared with the rates of spontaneous radiative emissions (upper dashed line) and with the rates of radiative absorptions (lower dashed line). As can be seen, below 400 km both radiative rates are smaller than the rates of elastic collisions and, therefore, we expect that in the low photosphere of the quiet Sun elastic collisions with neutral hydrogen atoms are efficient in destroying the atomic alignment that anisotropic radiation pumping introduce in the O I IR triplet levels. This is in fact the case, as shown by the self-consistent values of the $\rho^0_0(i)$ and $\rho^2_0(i)$ elements of the atomic density matrix we obtained by numerically solving the multilevel problem of the generation and transfer of scattering polarization in a semi-empirical model of the solar atmosphere. Fig. 3 shows the ensuing emergent fractional linear polarization for a close to the limb line of sight.

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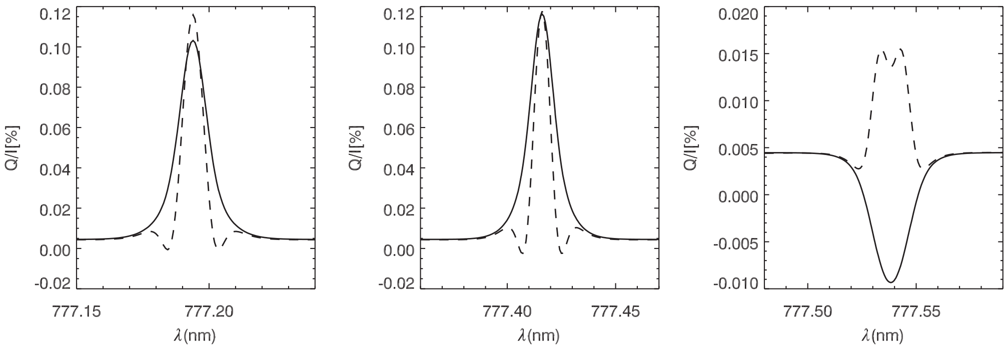

Figure 3. The Q/I profiles of the emergent radiation in the IR triplet of O I calculated in a semi-empirical model of the quiet solar atmosphere for a line of sight with $\mu = 0.1$. Dashed curves: without elastic collisions. Solid curves: with elastic collisions. The positive reference direction for Stokes Q is the parallel to the nearest limb. From Del Pino Alemán *et al.* (2015).

As seen in Fig. 3, only when the effect of elastic collisions is taken into account the theoretical Q/I profiles agree with the observations of Fig. 1. As clarified above (see Fig. 2), with elastic collisions the fractional alignment of the O I IR triplet levels is negligible in the solar photosphere, which is the atmospheric region where the Stokes I profiles of such lines originate. Therefore, the physical origin of the observed Q/I profiles must be the selective emission and selective absorption processes produced by the oxygen atoms in the layers above (see Del Pino Alemán *et al.* 2015). Interestingly, the Q/I profile of line 3 is dominated by "zero field" dichroism in the solar chromosphere. This result can be understood by using Eq. (2.5) and noting that $\sigma^2_0(l) \approx \sigma^2_0(u)$ for line 3, while $\mathcal{Z} \approx 0.6$ and $\mathcal{W} = 0.1$.

4. A key mechanism for understanding the scattering polarization of the Na I D$_1$ line

The solid curve of Fig. 4-a shows the observation by Stenflo & Keller (1997) of the scattering polarization across the Na I doublet. They considered the D$_1$ line signal enigmatic because the lower and upper levels of the line have $J = 1/2$, and levels with $J = 0$ or with $J = 1/2$ cannot carry atomic alignment. Landi Degl'Innocenti (1998) pointed out that for modeling the scattering polarization of the Na I D-lines it is necessary to take into account the HFS of sodium. He then considered the unmagnetized reference case and applied the metalevels theory (see Section 2.2) assuming that within the frequency interval spanned by the HFS components of each D-line the anisotropy of the pumping radiation field is constant (independent of frequency). He concluded that it is possible to explain the observed scattering polarization *only* if there is a substantial amount of atomic polarization in the HFS sublevels of the ground level of Na I (see the dotted lines in the left panels of Fig. 4). The ground level of Na I is long-lived and, therefore, very sensitive to depolarizing mechanisms, such as the Hanle effect of very weak fields. Therefore, and given the substantial amount of ground level polarization needed to fit the Q/I observation, Landi Degl'Innocenti (1998) concluded that the observed D$_1$ signal implies that inclined magnetic fields stronger than 0.01 G cannot exist in the lower chromosphere. He also pointed out that this is difficult to understand because there is evidence from other type of observations that the lower solar chromosphere is significantly more magnetized. This led to a paradox, which we may call the "sodium D$_1$ line paradox".

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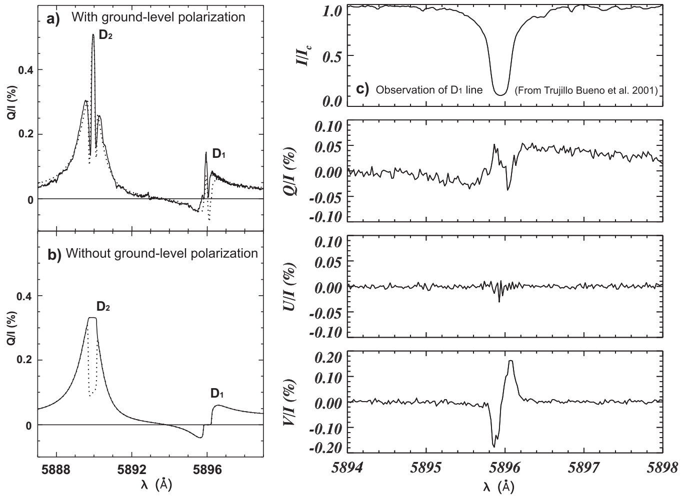

Figure 4. Observations of the scattering polarization in the Na I D-lines and theoretical modeling with a parametrized amount of ground-level polarization, and assuming constant radiation anisotropy within each D line. The solid curve of panel **(a)** shows the Q/I observed by Stenflo & Keller (1997) at $\mu = 0.05$. The dotted line is Landi Degl'Innocenti's (1998) ad-hoc fit accounting for HFS and ground-level polarization. The dotted curve of panel **(b)** shows the Q/I pattern calculated by Landi Degl'Innocenti (1998) when assuming that the ground-level is unpolarized, while the solid curve indicates the emergent Q/I when in addition the HFS of sodium is neglected. Panel **(c)** shows the full Stokes-vector THÉMIS observations by Trujillo Bueno *et al.* (2001) at $\mu = 0.1$.

In order to resolve the above-mentioned paradox we need a mechanism capable of introducing atomic polarization in the (short lived) upper F-levels of the D_1 line *without* the need of ground-level polarization. Belluzzi & Trujillo Bueno (2013) have identified such a mechanism by demonstrating that the small variations of the pumping D_1 line radiation between its very close HFS transitions is actually able to create a significant amount of atomic polarization in the upper F-levels of the D_1 lines of Ba II and Na I. To this end, their first step within the framework of the theory outlined in Section 2.2 consisted in assuming a two-level model atom with HFS, with unpolarized and infinitely sharp lower levels. The numerical solution of this problem give the Q/I profiles of Fig. 5. As seen in the left panel, the line-center amplitudes for relatively cool semi-empirical models like FAL-X are similar to the observations shown in the right panel of Fig. 4. Recently, Belluzzi *et al.* (2015b) have extended this work by including the quantum interference between the F-levels pertaining to the two upper J-levels of the sodium doublet, showing that the resulting Q/I pattern is very similar to high-sensitivity spectropolarimetric observations of the Na I D-lines, recently obtained using the Zürich Imaging Polarimeter (ZIMPOL) attached to the Gregory Coudé Telescope of IRSOL (Locarno; Switzerland).

5. Predictions

The spectral lines that originate in the upper chromosphere and transition region of the Sun lie in the far ultraviolet (FUV) and extreme ultraviolet (EUV) spectral regions, which can only be observed from space. It is therefore important to carry out theoretical investigations to estimate the significance of the scattering polarization signals and their magnetic sensitivity. A recent review on this topic with information on several FUV and EUV lines can be found in Trujillo Bueno (2014). Here we just show in Fig. 6 a

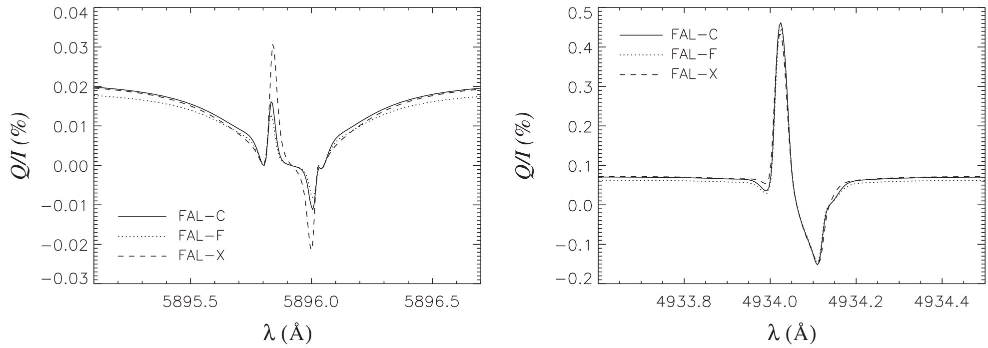

Figure 5. The scattering polarization of the D_1 lines of Na I (left panel) and Ba II (right panel) calculated without ground-level polarization, but taking into account the spectral structure of the pumping radiation field. The Q/I profiles correspond to calculations in the indicated semi-empirical models of the solar atmosphere. The positive reference direction for Stokes Q is the parallel to the nearest limb. From Belluzzi & Trujillo Bueno (2013).

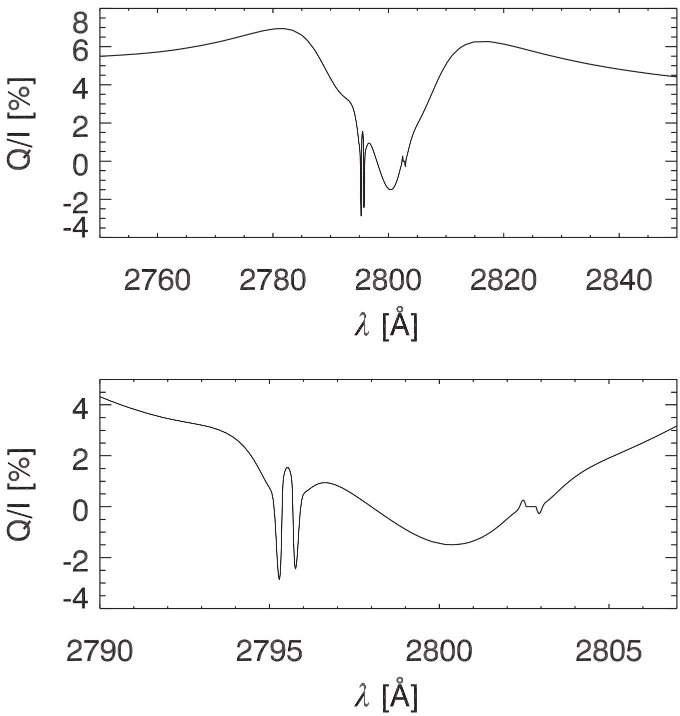

Figure 6. Scattering polarization pattern of the Mg II h & k lines, calculated in an unmagnetized semi-empirical model of the quiet solar atmosphere. The positive reference direction for Stokes Q is the parallel to the nearest limb.

theoretical prediction for the scattering polarization in the Mg II h & k lines, similar to that of Belluzzi & Trujillo Bueno (2012), but including the interaction between the line scattering processes and those responsible of the polarization of the Sun's continuous radiation (i.e., the Rayleigh and Thomson scattering processes that produce the Q/I values shown in the far wings seen in the upper panel of Fig. 6). Of particular interest is that at the center of the (intrinsically unpolarizable) h line we find $Q/I = 0$ (see the bottom panel), in spite of the fact that the redistribution of the spectral line radiation due to the non-coherence of the continuum scattering may in principle produce signals in intrinsically unpolarizable lines (see Del Pino Alemán *et al.* 2014). This is important because by measuring simultaneously the Mg II h & k lines one would have automatically a way to fix the zero offset of the polarization scale.

6. Concluding comments

The development of new facilities to carry out high-sensitivity spectropolarimetric observations is extremely important. Equally relevant is to infer correctly, from the measured spectral line intensity and polarization, the physical properties of the observed plasma. To this end, we need to combine and expand expertise on atomic physics, on the quantum theory of polarization, on advanced methods in numerical radiative transfer, and on the confrontation of spectropolarimetric observations with spectral synthesis in increasingly realistic models of stellar atmospheres.

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