Influence of atomic polarization and horizontal illumination on the Stokes profiles of the He I 10830Å multiplet

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ABSTRACT

The polarization observed in the spectral lines of the He I 10830 Å multiplet carries valuable information on the dynamical and magnetic properties of plasma structures in the solar chromosphere and corona, such as spicules, prominences, filaments, emerging magnetic flux regions, etc. Therefore, it is crucial to have a good physical understanding of the sensitivity of the observed spectral line polarization to the various competing physical mechanisms. Here we focus on investigating the influence of atomic level polarization on the emergent Stokes profiles for a broad range of magnetic field strengths, in both 90° and forward scattering geometry. We show that, contrary to a widespread belief, the selective emission and absorption processes caused by the presence of atomic level polarization may have an important influence on the emergent linear polarization, even for magnetic field strengths as large as 1000 G. Consequently, the modeling of the Stokes Q and U profiles should not be done by taking only into account the contribution of the transverse Zeeman effect within the framework of the Paschen-Back effect theory, unless the magnetic field intensity of the observed plasma structure is sensibly larger than 1000 G. We point out also that in low-lying optically thick plasma structures, such as those of active region filaments, the (horizontal) radiation field generated by the structure itself may substantially reduce the positive contribution to the anisotropy factor caused by the (vertical) radiation field coming from the underlying solar photosphere, so that the amount of atomic level polarization may turn out to be negligible. Only under such circumstances may the emergent linear polarization of the He I 10830 Å multiplet in such regions of the solar atmosphere be dominated by the contribution caused by the transverse Zeeman effect.

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1. Introduction

In order to obtain reliable empirical information on the strength and geometry of astrophysical magnetic fields we need to develop and apply suitable diagnostic tools within the framework of the quantum theory of spectral line polarization (e.g., the recent monograph by Landi Degl'Innocenti & Landolfi 2004). A naïve knowledge and/or an unjustified neglect of some of the physical mechanisms that produce polarization in spectral lines may lead to significant errors in our inferences and/or to missing the exciting opportunity of proposing new practical ideas for magnetic field diagnostics. In this respect, the main aim of this paper is to help clarify further the physics of the observed polarization in the spectral lines of the He I 10830 Å multiplet, because they contain precious information on the dynamical and magnetic properties of a variety of solar chromospheric and coronal structures.

The most important mechanisms that induce and modify polarization signatures in the spectral lines that originate in the atmospheres of the Sun and of other stars are the Zeeman effect, anisotropic radiation pumping and the Hanle effect (e.g., the recent review by Trujillo Bueno 2005).

The Zeeman effect requires the presence of a magnetic field, which causes the atomic and molecular energy levels to split into different magnetic sublevels characterized by their magnetic quantum number M. As a result, the wavelength positions of the π ($\Delta M = M_u - M_l = 0$), $\sigma_{\rm blue}$ ($\Delta M = +1$) and $\sigma_{\rm red}$ ($\Delta M = -1$) transitions do not coincide and, therefore, their respective polarization signals do not cancel out. The Zeeman effect is most sensitive in *circular* polarization (quantified by the Stokes V parameter), with a magnitude that for not too strong fields scales with the ratio between the Zeeman splitting and the width of the spectral line (which is very much larger than the natural width of the atomic levels!). This so-called *longitudinal* Zeeman effect responds to the line-of-sight component of the magnetic field. In contrast, the *transverse* Zeeman effect responds to the component of the magnetic field perpendicular to the line of sight, producing instead *linear* polarization signals (quantified by the Stokes Q and U parameters) that are normally below the noise level of present observational possibilities for intrinsically weak fields (typically B$\lesssim$100 gauss for solar spectropolarimetry).

The anisotropic illumination of the atoms in the outer regions of a stellar atmosphere may produce atomic level polarization (that is, population imbalances and/or quantum coherences between the magnetic sublevels pertaining to the upper and/or lower level of the line transition under consideration), in such a way that the populations of substates with different values of $|M|$ are different. This is termed *atomic level alignment*. Under such circumstances, the polarization signals of the π and σ transitions do not cancel out, even in the absence of a magnetic field, simply because the population imbalances among the magnetic sublevels imply more or less π transitions, per unit volume and time, than σ transitions. Interestingly, this atomic level polarization is modified by the presence of a magnetic field *inclined* with respect to the symmetry axis of the pumping radiation field (i.e., the Hanle effect; e.g., the review by Trujillo Bueno 2001). The magnetic field intensity (measured in gauss) that is sufficient to produce a sizable change in the atomic polarization of a given level is

$$B_H = \frac{1.137 \times 10^{-7}}{t_{\rm life}\, g_J}\,, \tag{1}$$

where $t_{\rm life}$ and g_J are, respectively, the level's lifetime (in seconds) and its Landé factor[1].

As discussed by Trujillo Bueno et al. (2002) a notable example of a multiplet whose spectral lines are sensitive to both effects (that is, to the Zeeman splitting and to the atomic level polarization) is the He I 10830 Å multiplet, whose Stokes profiles can be observed in a variety of plasma structures of the solar chromosphere and corona, such as sunspots (Harvey & Hall 1971; Rüedi et al. 1995; Centeno et al. 2006), coronal filaments (Lin et al. 1998; Trujillo Bueno et al. 2002), prominences (Trujillo Bueno et al. 2002; Merenda et al. 2006), emerging flux regions (Solanki et al. 2003; Lagg et al. 2004), chromospheric spicules (Trujillo Bueno et al. 2005a; Socas-Navarro & Elmore 2005), active region filaments (Martínez Pillet et al. 2006; in preparation) and flaring regions (Sasso et al. 2006).

The He I 10830 Å multiplet originates between a lower term ($2^3{\rm S}_1$) and an upper term ($2^3{\rm P}_{2,1,0}$). Therefore, it comprises three spectral lines: a 'blue' component at 10829.09 Å (with $J_l = 1$ and $J_u = 0$), and two 'red' components at 10830.25 Å (with $J_u = 1$) and at 10830.34 Å with ($J_u = 2$) which appear blended at solar atmospheric temperatures. Although the circular polarization of the He I 10830 Å lines is dominated by the longitudinal Zeeman effect, we expect their linear polarization to be the result of the joint action of the transverse Zeeman effect and of the atomic polarization that anisotropic radiation pumping processes induce in the helium levels. Actually, as we shall show in this paper, the degree of anisotropy of the solar continuum radiation at the wavelengths of the relevant helium transitions is

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[1] This basic formula of the Hanle effect results from equating the Zeeman splitting with the natural width (or inverse lifetime) of the energy level under consideration (which can be either the upper or the lower level of the chosen spectral line).

sufficiently important so as to produce a significant amount of atomic polarization in the lower and upper levels of the He I 10830 multiplet, even at relatively low atmospheric heights (e.g., $\sim$1000 Km). Elastic collisions with neutral hydrogen atoms are unable to destroy this atomic polarization that the anisotropy of the solar radiation field can (in principle) induce in the helium levels. Obviously, for sufficiently weak magnetic fields (e.g., for $B \lesssim 100$ G) the linear polarization is dominated by the *selective emission* and *selective absorption* of polarization components that result from the atomic level polarization (Trujillo Bueno et al. 2002). However, it would not be correct to give for granted that for relatively strong fields (say, for $B \approx 1000$ G) the linear polarization of the He I 10830 Å multiplet is going to be necessarily dominated by the transverse Zeeman effect.

Unfortunately, with very few exceptions (Trujillo Bueno et al. 2002, 2005a; Merenda et al. 2006), the modeling of spectropolarimetric observations of the He I 10830 Å multiplet has been carried out without taking into account that, in principle, the observed linear polarization may be actually the result of the joined action of the transverse Zeeman effect and of the atomic level polarization. To neglect *a priori* the influence of atomic level polarization simply because the considered point of the observed field of view is significantly magnetized is not justified. This is a reasonable approximation when the plasma diagnostics is being done via the analysis of only the Stokes I and V profiles, such as those measured in sunspot umbrae (e.g., Centeno et al. 2006), but it might not be so adequate in the case that Stokes Q and U are also considered, such as those observed by Solanki et al. (2003) and Lagg et al. (2004) in emerging flux regions.

A recent investigation has already pointed out that, even when only the contribution of the Zeeman effect is accounted for, the wavelength positions and the strengths of the π and σ components should be calculated in the incomplete Paschen-Back effect regime, given that the linear Zeeman effect theory *overestimates* the amplitudes of the emergent linear and circular polarization –that is, it *underestimates* the inferred magnetic field strength (Socas-Navarro, Trujillo Bueno & Landi Degl'Innocenti 2004). In this paper we focus instead on clarifying the role played by the presence of atomic level polarization on the emergent Stokes profiles of the He I 10830 Å multiplet for increasing values of the strength of the assumed magnetic field. As we shall see below, the influence of atomic level polarization on the Stokes Q and U profiles of the He I 10830 Å multiplet turns out to be significant, even for magnetic field strengths as large as 1000 G. In fact, as pointed out below, some of the Stokes profiles of emerging flux regions that Solanki et al. (2003) and Lagg et al. (2004) have interpreted in terms of the linear Zeeman effect theory neglecting atomic level polarization show, however, clear observational signatures of the presence of this physical ingredient. On the other hand, if any Stokes profiles observation of a moderately magnetized solar atmospheric region turns out to show no hint at all of the presence of atomic level polarization (such as it seems to be the case with the active region filament observations reported by V. Martínez Pillet and collaborators during the Fourth International Workshop on Solar Polarization) the reason, in our opinion, is to be found in the lower degree of anisotropy of the radiation field that pumps the helium atoms inside such elongated, optically-thick plasma structures.

The outline of this paper is as follows. The formulation of the problem is presented in Section 2, where we inform about the equations we have solved for calculating the emergent Stokes profiles from an optically thick slab located at a height of about 2000 Km above the solar visible “surface”. Section 3 shows several illustrative examples of the generated spectral line polarization when neglecting or taking into account the atomic level polarization induced by the photospheric continuum radiation. Section 4 investigates the extent to which the anisotropy of the photospheric radiation field may be modified by the radiation generated by the assumed plasma structure itself. Finally, in Section 5 we summarize the main conclusions of our work and insist on the scientific interest for spectropolarimetry from space.

2. Formulation of the problem

As illustrated in Fig. 1, we consider a constant-property slab of magnetized chromospheric material located at a height of only 3 arc seconds ($\sim$2000) km above the solar “visible” surface. The magnetic field, whose strength we will vary at will, is assumed to be horizontal (i.e., parallel to the solar “surface”). The slab's optical thickness at the wavelength and line of sight under consideration is τ, while the symbol $\Delta\tau_{\rm red}$ denotes the optical thickness of the slab along its normal direction at the line center of the red blended component. We have chosen $\Delta\tau_{\rm red} = 1$, which is just at the transition limit between an optically thin and an optically thick medium. All the atoms inside this slab are assumed to be illuminated by the unpolarized and limb-darkened photospheric radiation field whose center-to-limb variation has been tabulated by Pierce (2000). This implies that, for the moment, we are neglecting the influence of possible radiative transfer effects inside this $\Delta\tau_{\rm red} = 1$ slab on the anisotropy factor, whose definition is (Landi Degl'Innocenti & Landolfi 2004)

$$w = \sqrt{2}\frac{J^2_0}{J^0_0}\,, \tag{2}$$

where

$$J^0_0 = \frac{1}{4\pi}\int I_{\nu,\vec{\Omega}} d\vec{\Omega} \tag{3}$$

and

$$J^2_0 = \frac{1}{2\sqrt{2}}\frac{1}{4\pi}\int (3\mu^2 - 1) I_{\nu,\vec{\Omega}} d\vec{\Omega}, \tag{4}$$

with $\mu = \cos\theta$ (θ being the angle between the ray under consideration and the solar local vertical). Therefore, in a stellar atmosphere the possible values of the anisotropy factor vary between $w = -1/2$ for the limiting case of illumination by a purely horizontal radiation field without any azimuthal dependence, and $w = 1$ for purely vertical illumination. Two main factors contribute to the value of w at a given height in the *quiet* solar atmosphere: (1) the center to limb variation of the solar radiation field at the wavelength under consideration and (2) the geometrical effect due to the fact that, the larger the atmospheric height, the smaller the solid angle subtended by the solar visible sphere. We point out that, at a height of 3 arc seconds in the quiet solar atmosphere, $w = 0.097$ at 10830 Å, while $w = 0.040$ if only the above-mentioned geometrical effect is taken into account (that is, when the contribution due to the center-to-limb variation is disregarded).

The radiative transitions caused by the anisotropic illumination of the slab's helium atoms induce population imbalances and quantum coherences among the magnetic substates of the energy levels (that is, atomic level polarization), which we quantify by solving the statistical equilibrium equations for the multipole components, $\rho^K_Q(J, J')$, of the atomic density matrix (see Section 7.6a in Landi Degl'Innocenti & Landolfi 2004). We do this using a realistic model atom that includes the 5 lowest terms of the triplet system of neutral helium, which implies 11 J-levels and 6 transitions between the terms (see Fig. 13.9 in Landi Degl'Innocenti & Landolfi 2004). Such equations take fully into account the Hanle and Zeeman effects produced by the assumed horizontal magnetic field. We point out that we calculate the wavelength positions and the strengths of the Zeeman components in the incomplete Paschen-Back effect regime. From the calculated density-matrix elements it is then possible to compute the coefficients ϵ_I and ϵ_X (with $X = Q, U, V$) of the emission vector and the coefficients η_I, η_X, and ρ_X of the 4×4 propagation matrix of the Stokes vector transfer equation for a wavelength interval covering the 10830 Å multiplet (see Sections 7.6b in Landi Degl'Innocenti & Landolfi 2004).

The emergent Stokes vector $\mathbf{I}(\nu, \mathbf{\Omega}) = (I, Q, U, V)^\dagger$ (with †=transpose, ν the frequency and $\mathbf{\Omega}$ the line of sight) is given by the following expression, which can be easily obtained as a particular case of Eq. (27) of Trujillo Bueno (2003a):

$$\mathbf{I} = [\mathbf{1} + \Psi_0 \mathbf{K}']^{-1} \left[\left(e^{-\tau}\mathbf{1} - \Psi_M \mathbf{K}' \right) \mathbf{I}_{\rm sun} + (\Psi_M + \Psi_0)\mathbf{S} \right], \tag{5}$$

where $\mathbf{1}$ is the identity matrix and $\mathbf{I}_{\rm sun}$ the Stokes vector that illuminates the slab's boundary that is most distant from the observer, while $\mathbf{K}'$ and $\mathbf{S}$ are given by

$$\mathbf{K}' = \frac{\mathbf{K}}{\eta_I} - \mathbf{1}, \tag{6}$$

$$\mathbf{S} = \frac{\boldsymbol{\epsilon}}{\eta_I}. \tag{7}$$

In these expressions $\mathbf{K}$ is the propagation matrix of the Stokes vector transfer equation (whose elements are η_I, η_X and ρ_X; X being Q, U or V), while $\boldsymbol{\epsilon} = (\epsilon_I, \epsilon_Q, \epsilon_U, \epsilon_V)^\dagger$ is the emission vector. The coefficients Ψ_M and Ψ_0 depend only on the optical depth of the slab at the frequency and line-of-sight under consideration and their expressions are:

$$\begin{aligned} \Psi_M &= \frac{1-e^{-\tau}}{\tau} - e^{-\tau}, \\ \Psi_0 &= 1 - \frac{1-e^{-\tau}}{\tau}. \end{aligned} \quad (8)$$

It is of interest to note that when the anomalous dispersion terms are neglected in Eq. (5) (i.e., the ρ_X terms are taken equal to zero) we obtain

$$I(\tau) = I_0\,\mathrm{e}^{-\tau} + \frac{\epsilon_I}{\eta_I}(1 - \mathrm{e}^{-\tau}), \quad (9)$$

$$X(\tau) = X_0\,\mathrm{e}^{-\tau} + \frac{\epsilon_X}{\eta_I}(1 - \mathrm{e}^{-\tau}) - \frac{\epsilon_I \eta_X}{{\eta_I}^2}(1 - \mathrm{e}^{-\tau}) + \frac{\eta_X}{\eta_I}\tau\mathrm{e}^{-\tau}(\frac{\epsilon_I}{\eta_I} - I_0). \quad (10)$$

These approximate formulae for the emergent Stokes parameters coincide with those proposed by Trujillo Bueno et al. (2005a) for modeling the Hanle and Zeeman effects in solar chromospheric spicules and coronal filaments, which provide a very good approximation whenever $\epsilon_I \gg \epsilon_X$ and $\eta_I \gg (\eta_X, \rho_X)$. Although such inequalities are often met in solar spectropolarimetry (e.g., Sánchez Almeida & Trujillo Bueno 1999), all the calculations of this paper have however been carried out using the exact analytical solution given by Eq. (5), because they allow us to provide accurate results also for relatively high field strength values.

It is of interest to point out that Eqs. (9) and (10) simplify as follows for the optically thin and optically thick limiting cases:

(1) *Optically thin case* ($\tau \ll 1$)

$$I(\tau) \approx I_0 + \tau(S_I - I_0) \quad (11)$$

$$X(\tau) \approx X_0\,(1 - \tau) + \tau\big(S_I\,\frac{\epsilon_X}{\epsilon_I} - I_0\frac{\eta_X}{\eta_I}\big). \quad (12)$$

(2) *Optically thick case* ($\tau \gg 1$)

$$I(\tau) \approx S_I \quad (13)$$

$$X(\tau) \approx S_I \left(\frac{\epsilon_X}{\epsilon_I} - \frac{\eta_X}{\eta_I}\right), \quad (14)$$

where $S_I = \frac{\epsilon_I}{\eta_I}$.

3. The influence of atomic polarization

This section presents results for the two line of sights illustrated in Fig. 1: $\mu = 0$ and $\mu = 1$, where $\mu = \cos\theta$ (θ being the angle between the solar radius vector through the observed point and the line of sight). Therefore, $\mu = 0$ corresponds to the case of an off-limb observation (90° scattering geometry), while $\mu = 1$ to that of a solar disk center observation (forward scattering geometry). We point out that the boundary conditions are $I_0 = X_0 = 0$ for the 90° scattering case, but $I_0 = I_{\rm sun}(\mu = 1)$ and $X_0 = 0$ for the forward scattering case (with $I_{\rm sun}(\mu = 1)$ taken from Pierce (2000)).

Figure 2 shows the emergent Stokes profiles corresponding to the two lines of sight illustrated in Fig. 1. The left panels of Fig. 2 concern the 90° scattering or $\mu = 0$ case, which is typical of any off-limb observation. The right panels consider the forward scattering or $\mu = 1$ case, which is typical of an on-disk observation at or close to the center of the solar disk. In both cases we have assumed a constant-property slab with $\Delta\tau_{\rm red} = 1$ located at a height of only 3 arc seconds above the visible solar surface. As mentioned above, the magnetic field is assumed to be horizontal (i.e., parallel to the solar "surface") and oriented as indicated in Fig. 1 – that is, in a way such that also for the off-limb case the magnetic field vector is perpendicular to the line of sight. From top to bottom Fig. 2 shows the emergent Stokes profiles for increasing values of the magnetic strength and for the following three calculations of increasing realism:

(1) The dotted lines indicate the case without atomic level polarization. Here the only mechanism responsible for the emergent polarization is the Zeeman splitting of the upper and/or lower energy levels, which produces wavelength shifts between the π and σ components, whose positions and strengths have been calculated in the incomplete Paschen-Back effect regime. Therefore, zero polarization is found for $B = 0$ G.

(2) The dashed lines correspond to the case in which we have taken into account the influence of the atomic polarization of the two upper levels of the He I 10830 Å multiplet that can carry atomic level polarization -that is, those with $J = 2$ and $J = 1$. Therefore, in addition to the above-mentioned Zeeman effect contribution, we have here the possibility of a selective emission of polarization components, even for the zero field case. For example, this is the reason why the dashed line of the upper left panel of Fig. 2 shows a non-zero

linear polarization signal for the off-limb zero field case.

(3) The solid lines correspond to the most general situation in which the influence of the atomic polarization of the lower level is also taken into consideration, in addition to that of the upper levels and to the Zeeman effect. The consideration of lower-level polarization has two consequences. First, the amount of upper level polarization and the ensuing selective emission of polarization components is modified. Second, we can also have a selective absorption of polarization components. For instance, this is the reason why the blue line of the He I 10830 Å multiplet shows a non-zero linear polarization signal in the $B = 100$ G right panel of Fig. 2.

3.1. The weak field regime

As seen in Fig. 2, for magnetic strengths $B \lesssim 100$ gauss there is no significant contribution of the transverse Zeeman effect. In this *weak field* regime the emergent linear polarization is completely dominated by the atomic polarization of the lower and upper levels of the three line transitions involved. We emphasize that upper-level polarization leads to a *selective emission* of polarization components, while lower-level polarization to a *selective absorption* of polarization components (see Fig. 1).

As pointed out by Trujillo Bueno et al. (2002), selective absorption is the only mechanism that can produce linear polarization in the blue component of the He I 10830 Å multiplet. This is because the total angular momentum of its upper level is $J = 0$, which implies that, in the weak field regime under consideration, $\epsilon_Q = 0$. The reason why the off-limb panels of Fig. 2 with $B = 0$ and $B = 100$ gauss show no linear polarization in that blue line is that our slab with $\Delta\tau_{\rm red} = 1$ is optically thin at that blue wavelength, and also because Eqs. (11) and (12) with $I_0 = X_0 = 0$ imply

$$\frac{Q}{I} = \frac{\epsilon_Q}{\epsilon_I}, \tag{15}$$

which in the weak field regime is zero for the blue component of the helium multiplet (because its upper level, with $J = 0$, is intrinsically unpolarizable and $\epsilon_Q = 0$). Interestingly, the same Eqs. (11) and (12) indicate that, if the boundary intensity I_0 were non zero, then there should be a significant Q/I signal. In fact, this is the situation we have in all the right panels of Fig. 2, which correspond to simulated observations at solar disk center.

Obviously, due to symmetry reasons, forward scattering processes in the absence of a magnetic field produce zero polarization, as seen in the $B = 0$ gauss right panel of Fig. 2.

The same applies if there is a microturbulent magnetic field, or if the magnetic field vector is parallel to the symmetry axis of the radiation field that illuminates the slab's helium atoms. However, as shown in the $B = 100$ gauss right panel of Fig. 2, forward scattering processes in the presence of an inclined magnetic field do produce linear polarization in the lines of the He I 10830 Å multiplet. Here, the linear polarization is actually *created* by the Hanle effect. This is easy to understand by reasoning within the framework of the oscillator model for the Hanle effect in a triplet-type transition with $J_l = 0$ and $J_u = 1$ (e.g., Trujillo Bueno 2001). For the more general case of a line transition between two isolated levels having any possible J_l and J_u values, it is first necessary to recall (e.g., Landi Degl'Innocenti & Landolfi 2004) that the Hanle effect tends to destroy the quantum coherences between the magnetic sublevels pertaining to each J-level, *without modifying the population imbalances*[2]. In the magnetic field reference system, the quantum coherences (i.e., the ρ^K_Q values with $Q{\neq}0$) tend to vanish for magnetic strengths $B > B_{\rm satur}{\approx}10\,B_H$ (that is, in the saturation regime of the Hanle effect), so that in practice in this regime we are only left with the population imbalances among the magnetic sublevels pertaining to each J-level (i.e., with the ρ^K_Q values with $Q = 0$). Therefore, in the presence of a magnetic field inclined with respect to the symmetry axis of the pumping radiation field, the population imbalances of the upper and/or lower levels can produce linear polarization parallel or perpendicular to the horizontal component of the magnetic field vector, simply because of the ensuing selective emission and selective absorption of polarization components. The amplitude of the resulting Stokes Q signal can be easily estimated, in the optically thin limit of Eq. (12) and/or in the optically thick limit of Eq. (14), by introducing into such expressions the following approximate formulae (see Trujillo Bueno 2003b):

$$\frac{\epsilon_Q}{\epsilon_I} \approx \frac{3}{2\sqrt{2}}\,(1-\mu_B^2)\,\mathcal{W}\,\sigma^2_0(J_u)\,, \tag{16}$$

$$\frac{\eta_Q}{\eta_I} \approx \frac{3}{2\sqrt{2}}\,(1-\mu_B^2)\,\mathcal{Z}\,\sigma^2_0(J_l)\,, \tag{17}$$

where $\sigma^2_0 = \rho^2_0/\rho^0_0$ quantifies the degree of population imbalance of the J-level under consideration, while $\mathcal{W}$ and $\mathcal{Z}$ are numerical coefficients that depend on the J_l and J_u values[3]

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[2]This result is strictly valid for a two-level atomic model in the so-called magnetic field reference system, whose z-axis (i.e., the quantization axis for total angular momentum) is aligned with the magnetic field vector. We recall that once a reference system is chosen, the quantum coherences and the population imbalances can be conveniently quantified by using the multipole components of the atomic density matrix corresponding to the J-level under consideration, which are commonly denoted by the symbol $\rho^K_Q(J,J^{'})$.

[3]Actually, $\mathcal{W} = w^{(2)}_{J_uJ_l}$ and $\mathcal{Z} = w^{(2)}_{J_lJ_u}$, with $w^{(2)}_{JJ'}$ given by Eq. (10.12) of Landi Degl'Innocenti & Landolfi

(e.g., $\mathcal{W} = 0$ and $\mathcal{Z} = 1$ for a line transition with $J_l = 1$ and $J_u = 0$, $\mathcal{W} = 1$ and $\mathcal{Z} = 0$ for a line transition with $J_l = 0$ and $J_u = 1$, and $\mathcal{W} = \mathcal{Z} = -1/2$ for a line transition with $J_l = J_u = 1$). It is very important to note that in Eqs. (16) and (17) $\mu_B = \cos\theta_B$, where θ_B is *the angle between the magnetic field vector and the line of sight.*

Consider the case of our slab of chromospheric plasma at a given height above the visible solar "surface" and permeated by a horizontal magnetic field (see Fig. 1). A magnetic field of 100 gauss is more than sufficient to seriously reduce the quantum coherences (as quantified in the magnetic field reference frame), but is still sufficiently weak so as to be sure that the contribution from the transverse Zeeman effect is negligible. For the He I multiplet this happens for $10 \lesssim B \lesssim 100$ G, approximately. Under such circumstances the above-mentioned expressions should provide a reasonable approximation for estimating the emergent Q/I at the line center of a significantly strong spectral line. In agreement with our detailed numerical calculations such approximate formulae predict linear polarization for a disk center observation, be it for a line transition with $J_l = 1$ and $J_u = 0$, or for one with $J_l = 0$ and $J_u = 1$, or for one with non-zero J_l and J_u values (except the particular case of a spectral line with $J_l = J_u = 1/2$, because a level with $J = 1/2$ cannot be aligned).

3.2. The strong field regime

We now turn our attention to discussing the cases of Fig. 2 for which the transverse Zeeman effect plays a significant role -that is, those with $B \gtrsim 500$ gauss. As seen in the corresponding panels, the influence of atomic level polarization on the emergent linear polarization is significant, mainly for the red blended component (which results from two transitions whose upper levels can be polarized). As expected, the stronger the field the smaller the difference between the solid-line profiles (which show the joint effect of all physical ingredients) and the dotted profiles (which neglect the influence of atomic level polarization). The dashed profiles assume that the lower level is unpolarized, but take into account the selective emission processes that result from the presence of upper-level atomic polarization. For a slab with $\Delta\tau_{\rm red} = 1$ (which implies a smaller optical thickness at the wavelength of the blue line!) the influence of lower-level polarization is significant for the $B = 500$ gauss disk center case, but insignificant for sensibly stronger fields. However, upper-level polarization plays an important role on the linear polarization of the red blended component, even for magnetic strengths as large as 1000 gauss, for both the off-limb and on-disk cases. For example, for the $B = 500$ gauss case (which is representative of the strengths found in emerging flux regions)

(2004) for $K = 2$.

the accurately computed emergent Stokes Q profile is very different from that obtained taking into account only the influence of the transverse Zeeman effect within the framework of the Paschen-Back effect theory.

3.3. Observational evidence in emerging flux regions

Interestingly, the above-mentioned observational signature of the presence of atomic polarization in the helium levels is clearly seen in many of the Stokes profiles observed in emerging flux regions, such as those of Fig. 2 of Lagg et al. (2004). The solid lines of our Fig. 3 show a good theoretical fit to such observations (see Fig. 2 of Lagg et al. 2004), which we have obtained by taking into account the influence of atomic level polarization, in addition to that of the Zeeman effect. The dotted lines of Fig. 3 neglect, however, the influence of atomic level polarization. A comparison of such theoretical Stokes profiles with those observed by Lagg et al. (2004) indicates the presence of atomic level polarization in a relatively strong field region ($\sim$1000 gauss). It also shows that neglecting the influence of atomic level polarization on the emergent Stokes profiles is a suitable approximation for interpreting the circular polarization, but an unsuitable one for modeling the observed linear polarization. We conclude that the Stokes Q and U profiles observed by Lagg et al. (2004) in emerging flux regions are strongly modified by the presence of atomic level polarization, even at those atmospheric points of the observed field of view for which field strengths as large as 1000 gauss are inferred. In any case, it may be tranquilizing to point out that an inversion of the observed profiles neglecting atomic level polarization yields a similar magnetic field vector, in spite of the fact that the corresponding theoretical fit is very poor. A much better theoretical fit is automatically obtained when the influence of atomic level polarization is properly taken into account, which is important for the reliability of the Stokes inversion results (see Asensio Ramos & Trujillo Bueno 2006, in preparation, for a detailed description of our forward modeling and inversion codes we have applied in this investigation).

4. The influence of horizontal illumination

At the Fourth International Workshop on Solar Polarization (SPW4) that took place in Boulder (USA) during September 2005, V. Martínez Pillet and collaborators reported on spectropolarimetric observations of (low-lying) active region filaments in the He I 10830 Å multiplet, taken with the new version (TIP-2) of the Tenerife Infrared Polarimeter (Martínez Pillet et al. 2006; in preparation). In particular, in his SPW4 talk V. Martínez Pillet pointed out that the Stokes profiles of the observed active region filaments had the typical shape of polarization profiles produced by the Zeeman effect, without showing any hint at all of the observational signature of the Hanle effect in forward scattering that Trujillo Bueno et al. (2002) had found in solar coronal filaments located at relatively large heights above quiet regions of the solar "surface". In other words, the typical shapes of the linear polarization profiles observed by Martínez Pillet et al. in active region filaments were similar to those of the dotted lines of Fig. 3. He also reported that Hanle-effect signals similar to those found by Trujillo Bueno et al. (2002) were however present in the quiet regions of the observed field of view, outside the filament plasma.

Which could be the explanation of this enigmatic observational finding? One possibility is that elastic collisions with neutral hydrogen atoms completely destroy the polarization of the helium levels, but this is very unlikely because the typical densities of solar plasma structures are too low to affect the (short-lived) upper levels. In fact, simple estimates based on Eq. (7.108) of Landi Degl'Innocenti & Landolfi (2004) suggest that at a height of 2000 km in the FAL-C semi-empirical model of Fontenla et al. (1993) the upper-level rates of depolarizing collisions are about four orders of magnitude smaller than the corresponding Einstein A_{ul}-coefficient. Therefore, collisional depolarization seems to be indeed negligible, even if the hydrogen number density of active region filaments were three orders of magnitude larger than those of the FAL-C model at chromospheric heights. Another depolarizing possibility could be the bound-free transitions caused by the UV ionizing radiation coming downwards from the corona, but as is well known most of the ionizations take place from the singlet states of He I (instead of from the triplet states of the 10830 Å multiplet) and, in any case, the intensity of the ionizing radiation seems to be too low so as to produce any significant effect (Casini & Manso Sainz 2006; private communication).

In our opinion, what is happening here is that the radiation field generated by the active region filament itself (which is not an optically-thin structure!) makes a negative contribution to the anisotropy factor, so that the anisotropy of the true radiation field that illuminates the slab's helium atoms is negligible. In order to investigate this possibility we have calculated the anisotropy factor at each point inside a slab of total optical thickness $\tau_{\rm tot}$ in a way similar to that followed by Asensio Ramos, Landi Degl'Innocenti & Trujillo Bueno (2005), but taking into account the center-to-limb variation of the photospheric radiation field. If the center-to-limb variation is parameterized by the following functional form (Pierce 2000)

$$\frac{I(\mu)}{I(\mu=1)} = 1 - u(1-\mu) - v(1-\mu^2), \qquad (18)$$

the resulting expression for the anisotropy factor is[4].

[4]For simplicity, we write down the equation for the zero height case, while our Fig. 4 below is for a slab

$$w = \frac{1}{2}\frac{a + b(I_0/S_0)}{a' + b'(I_0/S_0)}, \tag{19}$$

where τ is measured starting at the lower boundary. The quantities a, b, a' and b' are given by:

$$\begin{aligned}
a &= \mathrm{E}_2(\tau) + \mathrm{E}_2(\tau_{\rm tot} - \tau) - 3\mathrm{E}_4(\tau) - 3\mathrm{E}_4(\tau_{\rm tot} - \tau) \\
b &= 3\mathrm{E}_4(\tau) - \mathrm{E}_2(\tau) + \Big[\mathrm{E}_2(\tau) - \mathrm{E}_3(\tau) - 3\mathrm{E}_4(\tau) + 3\mathrm{E}_5(\tau)\Big]u + \Big[\mathrm{E}_2(\tau) - 4\mathrm{E}_4(\tau) + 3\mathrm{E}_6(\tau)\Big]v \\
a' &= 2 - \mathrm{E}_2(\tau) - \mathrm{E}_2(\tau_{\rm tot} - \tau) \\
b' &= \mathrm{E}_2(\tau) - \Big[\mathrm{E}_2(\tau) - \mathrm{E}_3(\tau)\Big]u - \Big[\mathrm{E}_2(\tau) - \mathrm{E}_4(\tau)\Big]v.
\end{aligned} \tag{20}$$

The quantities u and v are the coefficients of the center-to-limb variation given by Pierce (2000), while $\mathrm{E}_n(\tau)$ is the exponential integral of order n. It is also interesting to point out that for the case of an isolated slab located at any given height above the solar "visible" surface the previous expression simplifies considerably, since it is given by

$$w = \frac{1}{2}\frac{a}{a'}. \tag{21}$$

Figure 4 shows how the anisotropy factor varies inside a slab of optical thickness $\tau_{\rm tot} = 1$, which is located at only 3 arc seconds above the visible "surface" and is illuminated from below by the continuum photospheric radiation. The results are shown for increasing values of the ratio I_0/S_0 (where $I_0 = I(\mu = 1)$ is the intensity of the vertical ray coming from the underlying photosphere, while $S_0 = S_I$ is the slab's source function). The dotted horizontal line indicates the value of the anisotropy factor, w, that we would have if the contribution of the radiation field generated by the slab itself were neglected. The remaining curves show the anisotropy factor for a range of I_0/S_0 values. As we can see, there is a range of I_0/S_0 values around $I_0/S_0 = 1$ (i.e., the expected values when the atomic excitation is dominated by radiative transitions) for which $w \approx 0$ at many points inside the slab. In our opinion, these are precisely the physical conditions inside the active region filaments observed by V. Martínez Pillet et al., which are elongated plasma structures located at relatively low heights above the visible solar "surface".

The illumination conditions in the emerging flux regions observed by Lagg et al. (2004) are clearly different. Here the illumination is due to the typical radiation field of a stratified atmosphere, whose anisotropy is dominated by the positive contribution caused by the limb

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located at 3 arc seconds above the solar visible "surface".

darkening of the outgoing radiation (e.g., Trujillo Bueno 2001). On the contrary, active region filaments are elongated plasma structures located at relatively low heights above the solar visible "surface". Such plasma structures "levitating" in the solar atmosphere have a significant optical thickness, which implies that we have to take into account the negative contribution to w caused by the (mainly) horizontal radiation field generated by the filament itself. If this reduction of the radiation field's anisotropy is not taken into account when doing inversions of the Stokes Q and U profiles observed in such type of optically-thick structures (that is, when only the positive anisotropy of the photospheric radiation field is considered), the inversion algorithm may artificially select magnetic field vectors with inclinations around the Van Vleck angle ($\theta_B = 54.74°$), because it is for this particular inclination that the contribution of atomic level polarization is minimized. Fortunately, the observed Stokes V profile is often available, but it is very unlikely that the observed linear polarization is automatically reproduced after choosing a magnetic strength that fits the observed circular polarization assuming that the magnetic field inclination is close to that of the Van Vleck angle. Obviously, when a spectropolarimetric observation of the He I 10830 Å multiplet does not show any hint at all of the presence of atomic level polarization, the best one can do for inferring the magnetic field vector is to apply an inversion code which takes only into account the Zeeman effect, but with the positions and strengths of the π and σ components calculated within the framework of the Paschen-Back effect theory.

5. Conclusions

Probably, one of our most interesting conclusions is that the modeling of the emergent Stokes Q and U profiles of the He I 10830 Å multiplet should not be done by neglecting the possible presence of atomic level polarization. Actually, the degree of anisotropy of the solar continuum radiation at 10830 Å is sufficiently important so as to produce a sizable amount of atomic alignment in the lower and upper levels of the He I 10830 Å multiplet, even at relatively low atmospheric heights such as 1000 Km.

For weak magnetic fields (e.g., $B \lesssim 100$ G) the emergent linear polarization is fully dominated by the *selective emission* and *selective absorption* of polarization components that result from this atomic level polarization. For stronger magnetic fields, the contribution of the transverse Zeeman effect cannot be neglected. However, the emergent linear polarization may still show an important contribution caused by the presence of atomic level polarization, even for magnetic strengths as large as 1000 G (see Fig. 2).

In emerging magnetic flux regions the anisotropic illumination of the helium atoms is expected to be more or less similar to that corresponding to a stratified stellar atmosphere, with the (mainly vertical) outgoing radiation contributing with positive values to the anisotropy factor, w, and with the (mainly horizontal) incoming radiation contributing with negative values. As a result, $w \approx 0.097$ at a height of 3 arc seconds in the quiet solar atmosphere and a significant amount of lower-level and upper-level polarization is induced by the ensuing radiative transitions. Interestingly, the observational signature of this atomic level polarization is clearly seen in many of the Stokes Q and U profiles observed by Lagg et al. (2004), even at points of the observed field of view for which magnetic strengths as large as 1000 G are inferred.

The illumination conditions are however different in optically thick plasma structures embedded in the solar atmosphere, such as those encountered in (low lying) active regions filaments. Here, in addition to the positive contribution to w due to the continuum radiation field coming from the underlying solar photosphere, we have to take into account the negative contribution caused by the radiation field generated by the optically-thick plasma structure itself. As a result, the anisotropy factor of the true radiation field that illuminates the helium atoms inside the filament plasma may be very different, as illustrated in Fig. 4 for the case of a constant-property slab of total optical thickness unity. Interestingly, for $I_0/S_0 \sim 1$ we find that $w \approx 0$ at many points inside the slab (with I_0 the intensity of the vertical ray of the photospheric radiation and S_0 the slab's source function). Under such circumstances the ensuing atomic level polarization turns out to be negligible and the emergent Stokes Q and U profiles are dominated by the transverse Zeeman effect. In our opinion, this is the main reason that explains the absence of any observational signature of the presence of atomic level polarization in the linear polarization profiles observed by Martínez Pillet and collaborators in active region filaments.

Finally, it is interesting to point out that for the case of isolated plasma structures located at any given height above the solar visible "surface" the anisotropy factor may reach a significant value (see the thin solid-line curve of Fig. 4, which corresponds to $I_0/S_0=0$). This suggests that a variety of plasma structures, like loops embedded in the 10^6 K solar corona, should produce measurable linear polarization even at spectral line wavelengths for which the underlying solar disk is seen completely dark (e.g., at the EUV and X-ray spectral regions). This last point emphasizes further the relevance of the scientific case for spectropolarimetry from space, so that space agencies worldwide should indeed try to open soon this new diagnostic window on the Universe.[5]

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[5]See Trujillo Bueno et al. (2005b) for additional arguments on the scientific case for spectropolarimetry from space.

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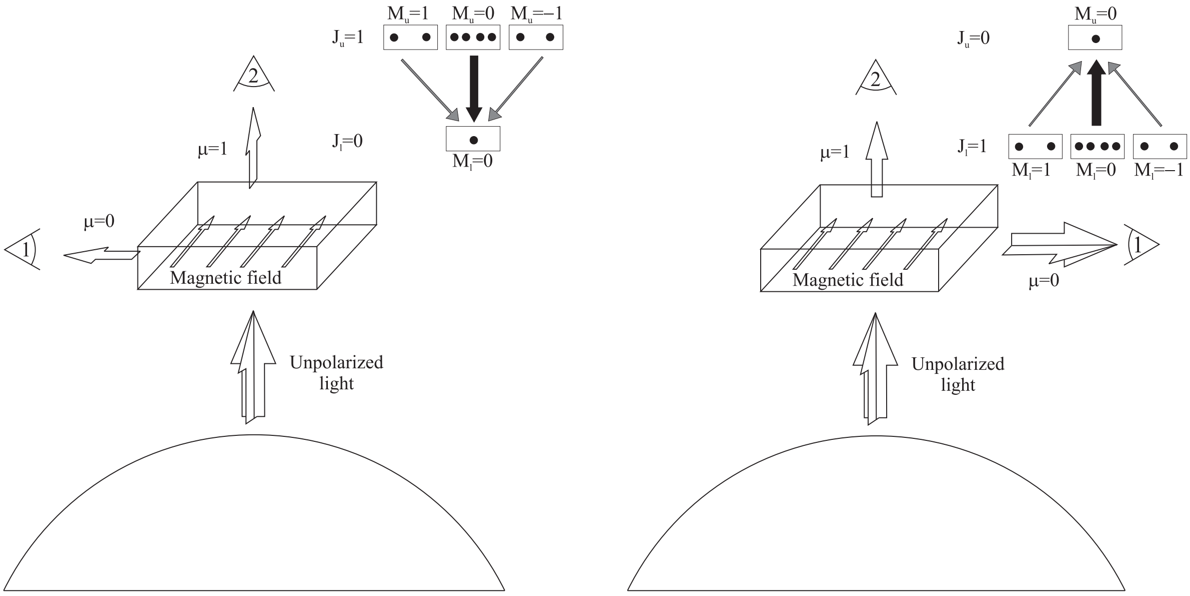

Fig. 1.— Illustration of the emergent polarization that results from 90° and from forward scattering events in the presence of a magnetic field parallel to the solar surface, which in this figure is assumed to be weak but still sufficiently strong so as to destroy any quantum coherences in the magnetic field reference frame (i.e., $10 \lesssim B \lesssim 100$ G). The left panel refers to a resonance line with $J_l = 0$ and $J_u = 1$, where we have assumed that the population imbalances are established by the resonance line radiation itself. The right panel refers to the "blue" line of the He I 10830 Å multiplet, which has $J_l = 1$ and $J_u = 0$, and for which the lower-level polarization is influenced by repopulation pumping (that is, by the spontaneous transitions from the polarized upper levels, with $J = 2$ and $J = 1$, of the He I 10830 Å multiplet; see Trujillo Bueno et al. 2002). Therefore, in the left panel the observed linear polarization is caused by *selective emission*, while in the right panel the only mechanism that can produce linear polarization is *selective absorption*. For this reason the observer at position "1" in the r.h.s. panel sees that the light scattered at 90° by the weakly-magnetized and optically-thin plasma is virtually unpolarized.

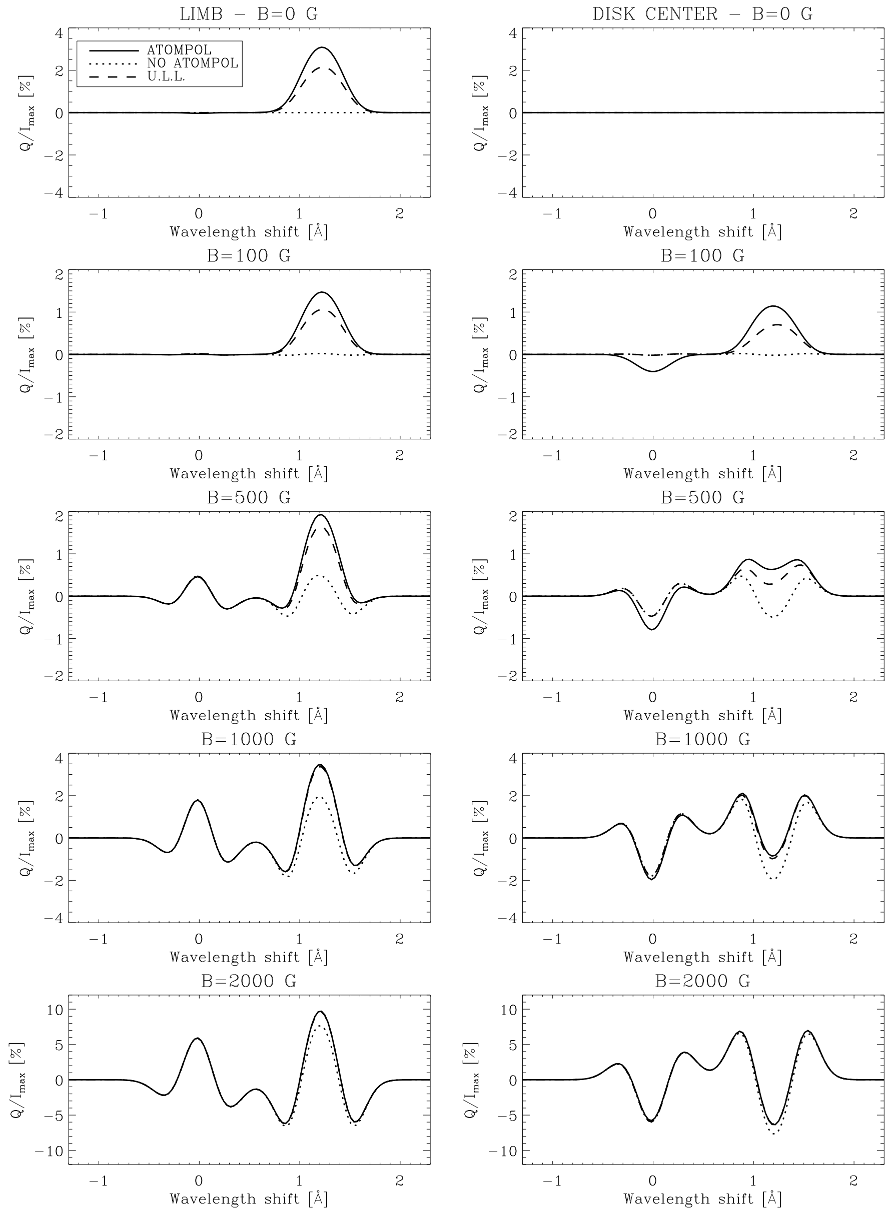

Fig. 2.— The emergent Stokes Q profiles of the He I 10830 Å multiplet calculated for the two line of sights illustrated in Fig. 1: 90° scattering (left panels, where the Stokes Q profile is normalized to the maximum line-core intensity of the Stokes I emission profile of the 'red' line) and forward scattering (right panels, where the Stokes Q profile is normalized to the maximum line-core depression of the Stokes I absorption profile of the 'red' line)). Each panel shows the results of three possible calculations for a given strength of the assumed horizontal magnetic field, whose orientation is as shown in Fig. 1 –that is, such that the magnetic field vector is always perpendicular to the line of sight. While the dotted lines neglect the influence of atomic level polarization, the solid lines take it fully into account. The dashed lines show what happens when only the lower level of the multiplet is assumed to be completely unpolarized. The calculations have been carried out for a thermal velocity $v_{\rm T} = 6.5\,{\rm km s^{-1}}$. The positive reference direction for Stokes Q is along the direction of the horizontal magnetic field.

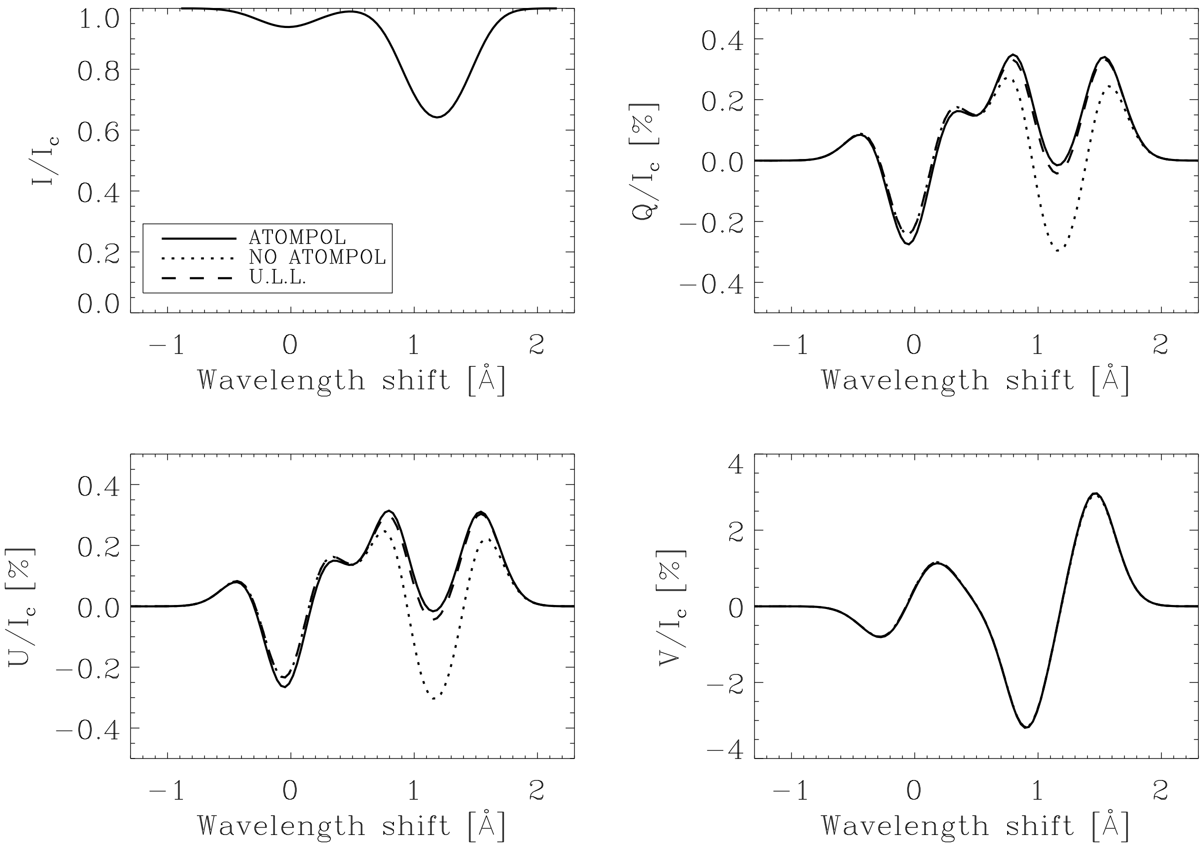

Fig. 3.— The emergent Stokes profiles in the He I 10830 Å multiplet calculated for the forward scattering case using the following parameters that resulted from the application of our Stokes inversion code: $\Delta\tau_{\rm red} = 0.87$, thermal velocity $v_{\rm T} = 8.36\,{\rm kms}^{-1}$, atmospheric height $h = 3''$, magnetic strength $B = 1070$ G, inclination $\theta_B = 86°$ and azimuth $\chi_B = -160°$. The positive reference direction for Stokes Q is along the x-axis with respect to which the magnetic field azimuth, χ_B, is measured. The Stokes profiles are normalized to the local continuum intensity. While the dotted lines neglect the influence of atomic level polarization, the solid lines take it fully into account. The dashed lines show what happens when only the lower level of the multiplet is assumed to be completely unpolarized. We point out that, within the framework of our modeling approach, the best fit to the observations shown by Lagg et al. (2004) in their Fig. 2 is provided by the solid lines.

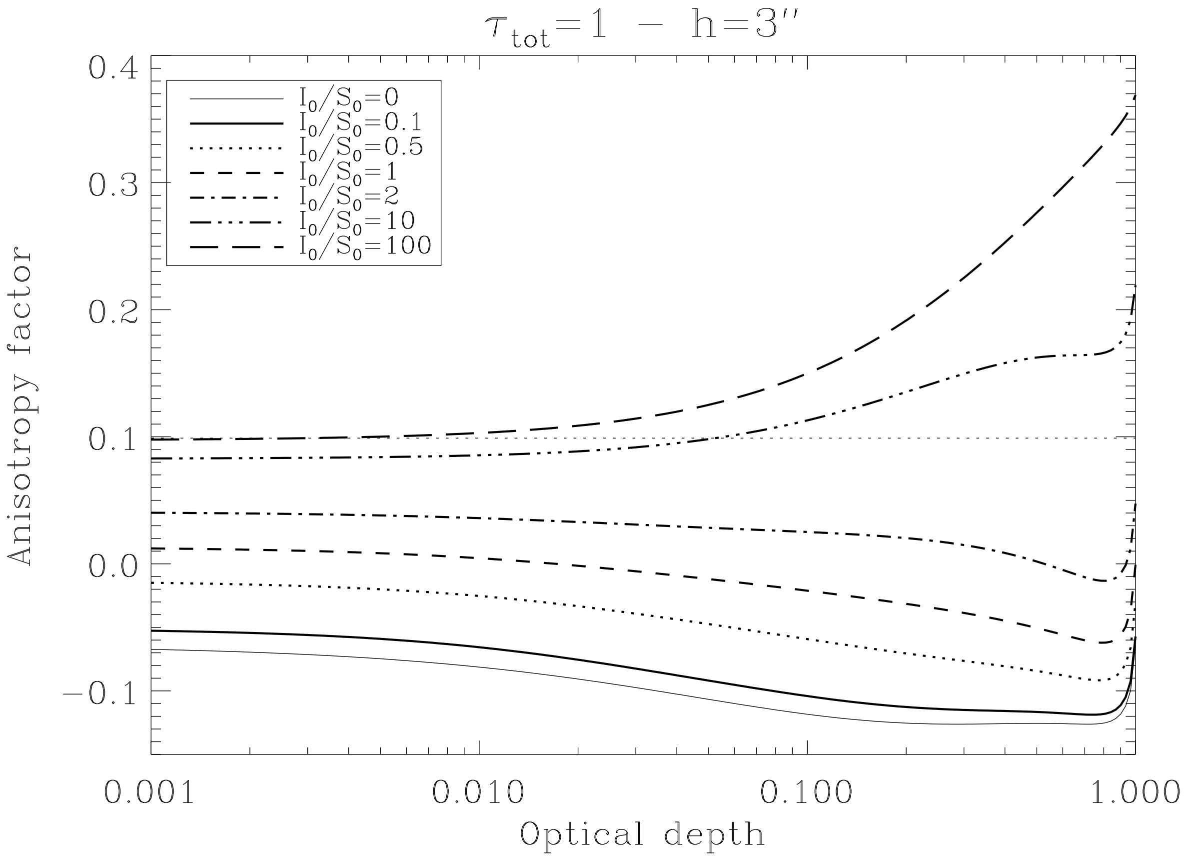

Fig. 4.— Variation of the anisotropy factor (see Eq. 2) inside a slab of total optical depth unity and source function S_0 located at a height of 3 arc seconds above the solar visible "surface". The lower boundary of the slab, from where the optical depth along the vertical direction is measured, is illuminated from below by the solar continuum radiation at 10830 Å, whose intensity at $\mu = 1$ is I_0. Each curve corresponds to the I_0/S_0 value indicated in the inset. Note that for $I_0/S_0 \approx 1$ (i.e., the expected value when the atomic excitation is dominated by radiative transitions) the anisotropy factor takes very small values at many points inside the slab. The dotted line indicates the value of the anisotropy factor corresponding to the case in which the contribution of the radiation field generated by the slab itself is neglected. Note that for the case of an isolated slab (see the thin solid-line curve corresponding to I_0/S_0=0) the anisotropy factor is negative and significant (actually, it is even more significant for slabs of smaller optical thickness).