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Chromospheric Magnetism and the Hanle Effect

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Abstract.

This article shows how some recent developments in the observation and theoretical modeling of weak polarization signals in chromospheric spectral lines are facilitating fundamental new advances in our ability to investigate the magnetism of the solar outer atmosphere via spectropolarimetry.

1. Introduction

The "quiet" solar chromosphere is a crucial region whose magnetism we need to understand for unlocking new discoveries in solar and stellar physics. It is in this highly inhomogeneous and dynamic region of low density plasma overlying the thin solar photosphere where the magnetic field becomes the globally dominating factor. If we aim at understanding the complex and time-dependent structure of the outer atmospheres of cool stars, we must first decipher how is the intensity and topology of the magnetic field of the solar chromosphere.

Over the last few years, observational investigations of scattering polarization on the Sun have pointed out the existence of "enigmatic" linear polarization signals in several spectral lines (observed in the "quiet" solar chromosphere close to the limb), which cannot be understood in terms of the classical theory of scattering polarization (Stenflo and Keller, 1997; Stenflo, Keller & Gandorfer, 2000; Trujillo Bueno et al., 2001*a*). These "enigmatic" features of the linearly-polarized solar-limb spectrum have motivated novel theoretical investigations of scattering polarization in spectral lines, which are now making feasible reliable confrontations between spectropolarimetric observations and multilevel radiative transfer simulations of the Hanle and Zeeman effects (Trujillo Bueno & Landi Degl'Innocenti, 1997; Landi Degl'Innocenti, 1998, 1999; Trujillo Bueno, 1999, 2001; Manso Sainz & Trujillo Bueno, 2001; Trujillo Bueno & Manso Sainz, 2001). Such investigations have been carried out within the framework of the density matrix polarization transfer theory (Landi Degl'Innocenti, 1982; 1983), which allows us to formulate scattering polarization problems taking into account a key physical ingredient that had been previously neglected: ground-level atomic polarization (i.e. the existence population imbalances and/or coherences among the Zeeman sublevels of the lower-level of the spectral line under consideration).

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Of particular interest in this respect is the letter published in Nature by Landi Degl'Innocenti (1998), whose title is "Evidence against turbulent and canopy-like magnetic fields in the solar chromosphere". He concluded that the explanation in terms of ground-level atomic polarization of the "enigmatic" linear polarization peaks of the sodium D-lines observed by Stenflo & Keller (1997) in quiet regions close to the solar limb implies that the magnetic field of the "quiet" solar chromosphere has to be either isotropically distributed but extremely low (with $B \lesssim 0.01$ gauss) or, alternatively, practically vertically orientated. In particular, magnetic fields stronger than 0.01 gauss either in the form of volume filling, turbulent fields or in the form of canopy-like, horizontal fields, were ruled out by Landi Degl'Innocenti in the layers of the "quiet" solar atmosphere where the cores of the sodium D-lines are formed. More recently, the personal conviction that magnetic fields of milligauss or weaker strength cannot exist in the highly conductive solar atmospheric plasma has led Stenflo et al. (2001) to the conclusion that the magnetic field in the most quiet regions of the solar chromosphere has then to be preferentially vertical.

The previous ideas about the intensity and orientation of the chromospheric magnetic field are in contradiction with the "standard picture" of chromospheric magnetism. According to this picture, there is "a layer of magnetic field which is directed parallel to the solar surface and located in the low chromosphere, overlying a field-free region of the solar photosphere". This so-called *magnetic canopy* "has a field strength of the order of 100 gauss and covers a large fraction of the solar surface" (see Steiner's 2001 contribution to the recently-published Encyclopedia of Astronomy and Astrophysics). This "standard picture" of chromospheric magnetism is based on chromospheric magnetograms and on extrapolations of photospheric magnetic flux tube models. The magnetograms were taken in network unipolar regions near the solar limb, as well as in sunspots and related active regions (Giovanelli 1980; Giovanelli & Jones 1982; Jones & Giovanelli 1983). The extrapolations assumed that the plasma inside the flux tube models is much hotter than the external medium (Solanki & Steiner, 1990). In an attempt to accomodate Landi Degl'Innocenti's (1998) conclusion with the "standard picture" of chromospheric magnetism, Schrijver & Zwaan (2000) argue that, presumably, the formation region of the D-lines of sodium "is just below the canopy, yet well above the turbulent photospheric internetwork field of some 10 gauss, whose typical strength is expected to drop off rapidly with height".

It is however very important to point out that, as pressed with great force by a working group on chromospheric fields (see Jones, 1985), chromospheric magnetograms have never detected magnetic canopies in the truly quiet Sun where the network is fragmentary and photospheric magnetograms show the well-known "salt and pepper" patterns of mixed polarity. In fact, the Ca II IR triplet and other chromospheric lines are relatively broad, which implies that the magnetic fields of the "quiet" chromospheric regions are very difficult to diagnose via the only consideration of the longitudinal Zeeman effect on which magnetograms are based on. Obviously, the above-mentioned chromospheric magnetograms (of network and active regions) and magnetohydrostatic extrapolations (of photospheric magnetic flux tube models) are not suitable for drawing conclusions on the magnetism of the most quiet regions of the solar chromosphere. In any case, recent observations of scattering polarization on the Sun using spectral lines whose lower level cannot be polarized (because its total angular momentum value is $J_l = 0$) seem to contain hints of Hanle depolarization that suggest the existence of turbulent and/or canopy-like horizontal fields having intensities in the range of gauss (Bianda, Stenflo & Solanki, 1999).

On the other hand, it is also necessary to point out that Landi Degl'Innocenti (1998) reached the above-mentioned conclusion for the Na I D-lines by adjusting free parameters within the framework of a heuristic approach to the problem of frequency redistribution, and by using expressions for the Stokes Q components of the emission vector and of the absorption matrix that are suitable for the *zero* magnetic field reference case. His conclusion that the magnetic field of the "quiet" solar chromosphere cannot be stronger than about 0.01 gauss unless it is oriented fairly close to the radial direction was reached on the basis of the sizeable amount of the ground-level polarization required for fitting the Q/I observations of Stenflo & Keller (1997), and on the basis of the assumption that the atomic polarization of the ground-level of sodium has to be sensitive to much weaker magnetic fields than the atomic polarization of the upper levels.

The previous introductory paragraphs illustrate the considerable confusion and paradoxical situation that presently exists in the field. Obviously, the only way to obtain reliable empirical information on the intensity and topology of the magnetic fields of the outer solar atmosphere (chromosphere, transition region, corona) is via the measurement and rigorous physical interpretation of polarization signals in suitable spectral lines. The present article shows how some recent advances in the observation and multilevel radiative transfer modeling of weak polarization signals in terms of the Hanle and Zeeman effects are creating a new picture of chromospheric magnetism.

2. Optical Pumping, Atomic Polarization, and the Hanle Effect

While the observed Stokes V signals are mainly due to the longitudinal Zeeman effect, the physical origin of the *linear* polarization signals that can be observed in solar prominences, filaments and in "quiet" regions close to the solar limb has nothing to do with the transverse Zeeman effect. The observed Stokes Q and U profiles are due to *atomic polarization*, i.e. to the existence of population imbalances and quantum interferences (or coherences) among the sublevels pertaining to the upper and/or lower atomic levels involved in the line transition under consideration. This *atomic polarization* is the result of a transfer process of "order" from the radiation field to the atomic system (see Trujillo Bueno, 2001). The most obvious manifestation of "order" in the radiation field of a stellar atmosphere is its degree of anisotropy, i.e. its center-to-limb variation, which produces anisotropic radiation pumping. This pumping is selective, in the sense that it produces population imbalances and quantum interferences (or coherences) among the Zeeman sublevels of each atomic level. This implies sources and sinks of linear (and even circular) polarization at each point within the medium. These locally generated polarization signals are then modified via transfer processes in the stellar plasma. The observed polarization signals are weak because the degree of anisotropy of the solar radiation field is weak (which leads to population imbalances and coherences that are small compared with the overall population of the atomic level under consideration), but also because we have collisions and magnetic fields which tend to modify the atomic polarization.

There are various pumping mechanisms capable of inducing atomic polarization (see the review by Trujillo Bueno, 2001)[1]. The presence of a magnetic field (which leads to a splitting of the atomic energy levels) is not necessary for the operation of such pumping processes, which can be particularly efficient if the depolarizing rates due to elastic collisions are sufficiently low. For example, **lower-level depopulation pumping** occurs when some *lower-state* sublevels absorb light more strongly than others. As a result, an excess population tends to build up in the weakly absorbing sublevels. For instance, as illustrated in Fig. 1, if an unpolarized light beam propagating along the direction chosen as the quantization axis illuminates a gas of two level atoms with $J_l = 1$ and $J_u = 0$, only the transitions corresponding to $\Delta M = \pm 1$ are effective, so that no transitions can occur out of the $M = 0$ sublevel of the lower level. On the other hand, the spontaneous de-excitation from the upper level populates with equal probability the three sublevels ($M = -1, 0, +1$) of the *lower* level. In the absence of any relaxation mechanisms, the final result of this optical-pumping cycle is that all atoms will eventually be pumped into the $M = 0$ sublevel of the *lower* level, and the medium will become transparent. On the contrary, **upper-level population pumping** occurs when some *upper-state* sublevels have more chances of being populated than others. Finally, **repopulation pumping** occurs when the lower-level is repopulated as a result of the spontaneous decay of a *polarized* upper-level.

The Hanle effect is the modification of the atomic polarization (and of the ensuing *linear* polarization profiles $Q(\lambda)$ and $U(\lambda)$) due to the action of a weak magnetic field (see the review by Trujillo Bueno, 2001). As the Zeeman sublevels of degenerate atomic levels are split by the magnetic field, the degeneracy is lifted and the coherences (and, in general, also the population imbalances among the sublevels) are modified. Therefore, the Hanle effect is sensitive to magnetic fields such that the corresponding Zeeman splitting is comparable to the inverse lifetime (or natural width) of the lower or the upper atomic levels of the line transition under consideration. On the contrary, the Zeeman effect is most sensitive in *circular* polarization (quantified by the Stokes V parameter), with a magnitude that 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), and in a way such that the V profile changes its sign for opposite orientations of the magnetic field vector.

The basic approximate formula to estimate the *maximum* magnetic field intensity B (measured in gauss) to which the Hanle effect can be sensitive is

$$10^6 \; B \; g_J \;\approx\; 1/t_{\rm life} \;, \tag{1}$$

where g_J and $t_{\rm life}$ are, respectively, the Landé factor and the lifetime (in seconds) of the atomic level under consideration (which can be either the upper or the lower level of the chosen spectral line transition). This formula shows that the

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[1] Note that there is a typing error in Eq. (11) of Trujillo Bueno (2001), since the inequality given by Eq. (11) is correct for $2\mathcal{A}$ and *not* for $\mathcal{A}$, as it was typed.

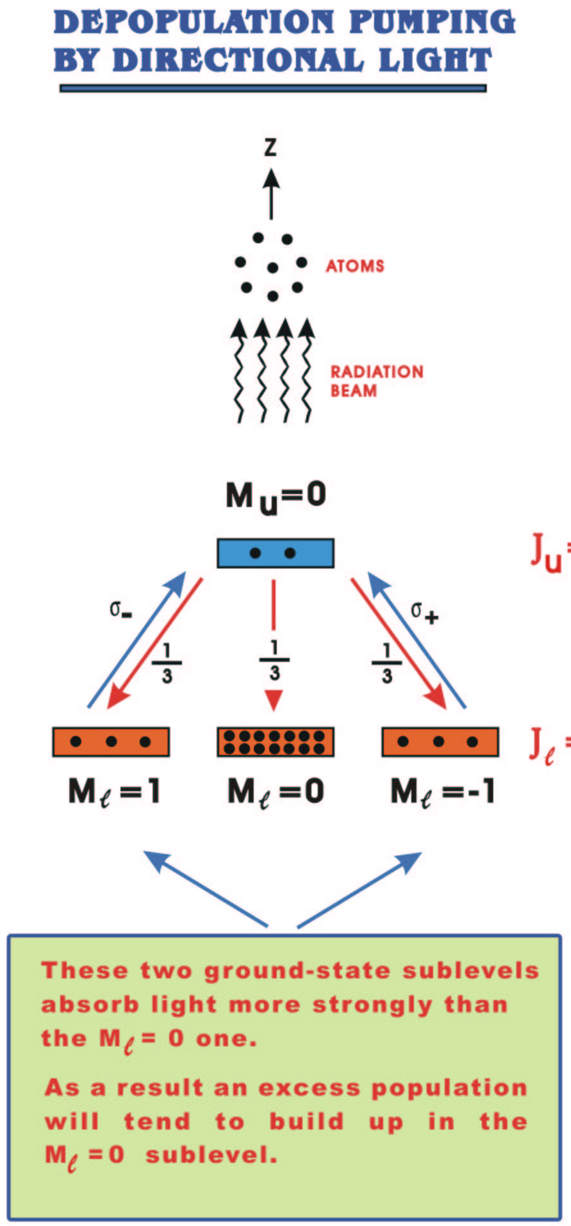

Figure 1. Illustration of the lower-level depopulation pumping mechanism producing lower-level atomic polarization.

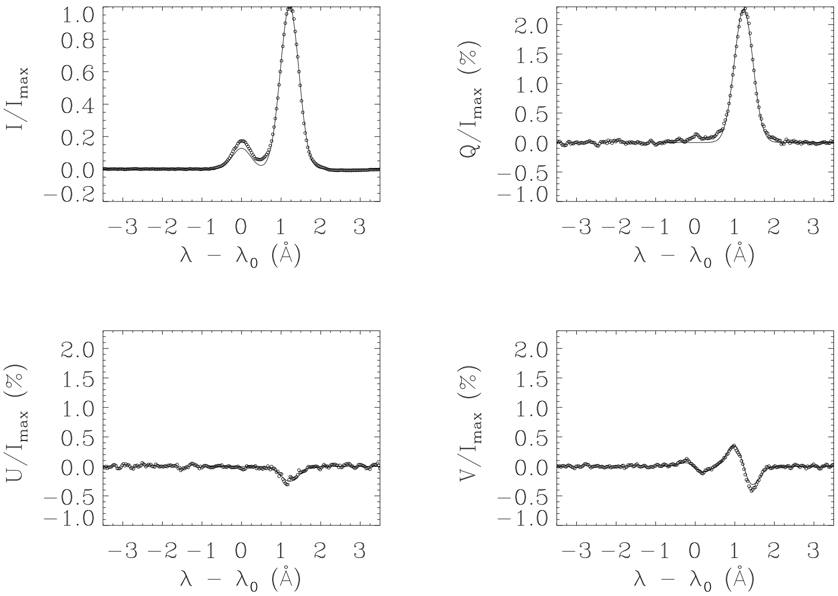

Figure 2. Prominence spectropolarimetric observation (open circles) versus theoretical modeling (solid line). The observed prominence region was located at a height of 20″ above the visible solar limb. The fit to the observations was done assuming a magnetic field vector with intensity B=40 gauss, inclination $\theta_{\rm B} = 31°$, and azimuth $\chi_{\rm B} = 176°$. The positive reference direction for Stokes Q is perpendicular to the radial direction through the observed point. $\lambda_0 = 10829.09$ Å is the line-center wavelength of the "blue" component of the He I 10830 Å multiplet. The Stokes profiles are normalized to the maximum line-core intensity of the "red" emission line. From Trujillo Bueno et al. (2001*b*).

measurement and physical interpretation of weak polarization signals in suitably chosen spectral lines may allow us to diagnose magnetic fields having intensities between 10^{-3} and 100 gauss approximately, i.e. in a parameter domain that is very hard to study via the Zeeman effect alone.

Let us now consider the case of a solar prominence, where the anisotropic illumination of the atomic system is more or less similar to that of the academic case of Fig. 1. Using the Tenerife Infrared Polarimeter (TIP) attached to the Vacuum Tower Telescope we have recently measured the full Stokes vector of the He I 10830 Å multiplet in a variety of prominences and filaments (see Trujillo Bueno et al., 2001*b*). The He I 10830 Å multiplet originates between a lower term 2^3S_1 and an upper term $2^3P_{2,1,0}$. Therefore, it has three components: a "blue" line at λ10829.09 with $J_l = 1$ and $J_{u_3} = 0$, and two "red" lines at λ10830.25 (with $J_{u_2} = 1$) and at λ10830.34 (with $J_{u_1} = 2$) which appear blended at the plasma temperatures of prominences. Fig. 2 shows the four Stokes parameters observed in a prominence that was located at about 15000 km above the visible solar limb (see the open circles). The solid line gives the result of our theoretical modeling, which is fully based on the density matrix theory for the multiterm atom (see Landi Degl'Innocenti, 1982). From the fitting to the spectropolarimetric observation of the observed prominence we infer a magnetic field of about 40 gauss, inclined by 31° with respect to the radial direction through the observed point.

It is interesting to point out that the "blue" component of the He I 10830 Å multiplet does not show any significant linear polarization. However, there are very significant Stokes Q and U signals around the wavelengths of the blended "red" components. These linear polarization signals are nothing but the observational signature of the atomic polarization of the *upper* levels with $J_{u_1}=2$ and $J_{u_2}=1$, i.e. they are exclusively due to the spontaneous emission which follow the anisotropic radiative excitation. In fact, the Stokes Q and U components of the line emission vector are given by (see Trujillo Bueno, 2001; with details and references therein):

$$\begin{aligned}\epsilon_Q = \epsilon_0\, w^{(2)}_{J_uJ_l}\Big\{ &\frac{3}{2\sqrt{2}}(\mu^2-1)\rho^2_0 - \sqrt{3}\mu\sqrt{1-\mu^2}(\cos\chi \mathrm{Re}[\rho^2_1] - \sin\chi \mathrm{Im}[\rho^2_1]) \\ &- \frac{\sqrt{3}}{2}(1+\mu^2)(\cos 2\chi\, \mathrm{Re}[\rho^2_2] - \sin 2\chi\, \mathrm{Im}[\rho^2_2])\Big\}, \qquad (2)\end{aligned}$$

$$\begin{aligned}\epsilon_U = \epsilon_0\, w^{(2)}_{J_uJ_l}\sqrt{3}\,\Big\{ &\sqrt{1-\mu^2}(\sin\chi \mathrm{Re}[\rho^2_1] + \cos\chi \mathrm{Im}[\rho^2_1]) \\ &+ \mu(\sin 2\chi\, \mathrm{Re}[\rho^2_2] + \cos 2\chi\, \mathrm{Im}[\rho^2_2])\Big\}, \qquad (3)\end{aligned}$$

where the ρ^2_Q symbols indicate the elements of the atomic density matrix of the *upper* level of the line transition under consideration. Note also that $\epsilon_0 = (h\nu/4\pi)A_{ul}\phi_x\mathcal{N}\sqrt{2J_u+1}$ (with $\mathcal{N}$ the total number of atoms per unit volume), that $w^{(2)}_{J_uJ_l}$ is the symbol introduced by Landi Degl'Innocenti (1984) (which depends only on J_u and J_l), and that the orientation of the ray is specified by $\mu=\cos\theta$ (with θ the polar angle) and by the azimuthal angle χ.

On the other hand, the Stokes Q and U components of the absorption matrix (i.e. η_Q and η_U) are given by identical expressions (i.e. by $\eta_Q=\epsilon_Q$ and by $\eta_U=\epsilon_U$), but with $\eta_0=(h\nu/4\pi)B_{lu}\phi_x\mathcal{N}\sqrt{2J_l+1}$ instead of ϵ_0, $w^{(2)}_{J_lJ_u}$ instead of $w^{(2)}_{J_uJ_l}$ and with the ρ^2_Q values of the *lower* level of the line transition (instead of those of the upper level). Note that ϵ_Q and η_Q depend on both the population imbalances (ρ^2_0) and on the coherences (ρ^2_Q, with $Q=1,2$), while ϵ_U and η_U depend *only* on the coherences. For instance, for a level with total angular momentum $J=1$ the *alignment* coefficient $\rho^2_0=\frac{1}{\sqrt{6}}[N_1-2N_0+N_{-1}]$ (where N_i indicates the populations of the Zeeman sublevels having magnetic quantum numbers $M=i$). The ρ^2_Q elements with $Q\neq0$ are *complex* numbers given by linear combinations of the quantum interferences (or coherences) between Zeeman sublevels whose magnetic quantum numbers differ by Q.

It becomes now clear why the emission process does *not* produce any significant *linear* polarization in the "blue" line (which has $J_u=0$ and $J_l=1$).

Simply because $\epsilon_Q{\approx}0$ and $\epsilon_U{\approx}0$. They are virtually zero because the upper level, having $J_u = 0$, cannot harbour any atomic polarization (i.e. $\rho^2_Q(\mathrm{up}) = 0$). The only possible non-vanishing contribution to ϵ_Q and ϵ_U comes from the Zeeman splitting of the lower level whose $J_l = 1$ (which is not accounted for by Eqs. 1 and 2), but this *transverse* Zeeman effect contribution is negligible for the weak magnetic fields of solar prominences (B $\lesssim$ 100 gauss).

However, we should recall that the transfer equation for Stokes Q that applies to the physical conditions of solar prominences and filaments is[2]

$$\frac{d}{ds}\,Q = [\epsilon_Q - \eta_Q\;I] - \eta_I\;Q\,, \tag{4}$$

where s is the geometrical distance along the ray. We can interpret this transfer equation for the Stokes Q-parameter as one having two contributions to the "effective emissivity": the first is given by the Q-component of the emission vector (ϵ_Q) and the second is related with the Q-component of the absorption matrix ($-\eta_Q I$). This shows that for line transitions whose upper level is intrinsically unpolarizable the terms $-\eta_Q\,I$ and $-\eta_U\,I$ are the only ones which play the role of the emissivity in Stokes Q and U at each point along the line of sight. This type of lines (which have $J_u = 0$ or $J_u = 1/2$) may be called "null" lines, because the spontaneously emitted radiation that follows the anisotropic radiative excitation is vitually *unpolarized*. Two interesting examples considered in this paper are the "blue" line of the He I 10830 Å multiplet (which has $J_u = 0$ and $J_l = 1$), and the 8662 Å line of the Ca II IR triplet (which has $J_u = 1/2$ and $J_l = 3/2$). Since the lower levels of such lines have total angular momentum values that allow them to carry atomic polarization, we have that η_Q and η_U can (in principle) end up having sizeable values. As pointed out below, this is indeed the case in the outer solar atmosphere.

Why have we not detected then any significant *linear* polarization in the above-mentioned "blue" line ? Because solar prominences are observed off-the-limb (i.e. against the *dark* background of the sky), which means that the Stokes I parameter along the line of sight is negligible. As a result, $\eta_Q\,I{\approx}0$ and $\eta_U\,I{\approx}0$. In other words, only if the observed prominence is sufficiently optically thick along the line of sight can we expect to detect a significant linear polarization signal in that "blue" line.

Why do we know then that there exists a siseable amount of atomic polarization in the lower level of the He I 10830 Å multiplet ? Because in our spectropolarimetric observations of solar filaments (i.e. "prominences" seen against the *bright* background of the solar disk!) we do detect a linear polarization signal in the "blue" line with an amplitude that is of the same order of magnitude as that corresponding to the "red" line (see Trujillo Bueno et. al., 2001*b*). This demonstrates that there indeed exists a sizeable amount of atomic polarization in the lower level of the He I 10830 Å multiplet (i.e. in the term 2^3S_1).

The *linear* polarization that we see in that "blue" line when observing solar filaments is nothing, but the observable effect of that lower-level atomic polarization. At this stage, it is crucial to point out that such a lower level is

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[2] The transfer equation for the Stokes U parameter is identical to the previous one, but with U instead of Q.

metastable, i.e., it is a relatively long-lived atomic level whose atomic polarization is vulnerable (via the lower-level Hanle effect) to magnetic fields of very low intensity ($\sim 10^{-3}$ gauss !). In other words, as shown in detail by Trujillo Bueno et al. (2001*b*), the polarization of metastable atomic levels, which is induced by optical pumping processes, can survive sufficiently and generate observable polarization signatures in the presence of the highly inclined magnetic fields with strengths in the gauss range that are characteristic of such plasma ribbons embedded in the solar corona.

It is also important to note in Fig. 2 that there are sizable circular polarization Stokes-V signals in both the blue and red components. They are due to the longitudinal Zeeman effect. Their detection is essential for the determination of the intensity of the magnetic field, because for fields larger than only a few gauss the He I 10830 Å multiplet enters into the saturated Hanle-effect regime for the upper level, where the linear polarization signals are sensitive only to the orientation of the magnetic field vector. Finally, it may be of interest to mention that the results of Fig. 2 may help also to illustrate the diagnostic method by means of which we should be able to investigate in the near future the magnetic fields of the solar corona via spectropolarimetric observations of coronal forbidden lines (see, e.g., Casini & Judge, 1999).

3. The "Enigmatic" Polarization Signals of the Ca II IR Triplet in the "Quiet" Solar Chromosphere

Solar prominences and filaments are located tens of thousands of kilometers above the visible solar "surface" and their confining magnetic field is "deterministic" (i.e. it does not have a random azimuthal component over the spatio-temporal resolution element of the observations). Therefore, one may wonder whether the atomic polarization of long-lived atomic levels can also be sufficiently significant in the solar chromosphere where the degree of anisotropic illumination of the atomic system is substantially lower and the magnetic field topology might be considerably more complex.

Fig. 3 shows the full Stokes vector of the Ca II 8662 Å line observed on the disk at 5″ from the solar limb. This observation is the result of a collaboration between Dittmann, Semel and Trujillo Bueno. We used Semel's stellar polarimeter attached to the Tenerife Gregory Coudé Telescope and carried out during September 2000 spectropolarimetric observations of the Ca II IR triplet in regions near the limb with varying degrees of magnetic activity. The Ca II 8662 Å line is of particular interest here because its upper level, having $J_u = 1/2$, cannot carry any atomic alignment. This is the reason which led Stenflo et al. (2000) to consider their detection of a significant Stokes Q/I amplitude in this spectral line as "enigmatic", because it was taken for granted that the emergent polarization signals can only come from the population imbalances and coherences in the *excited* states of the scattering process. The full Stokes vector observation of Fig. 3 shows the existence of sizable linear polarization signals in the Ca II 8662 Å line, both in Q/I and U/I. Their physical origin is the presence of a sizable amount of atomic polarization in the $^2\mathrm{D}_{3/2}$ metastable lower-level, which can produce significant values of $\eta_Q\, I$ and $\eta_U\, I$ if the Stokes-I intensity along the line of sight is also important enough (as it occurs for the on-the-disk observations

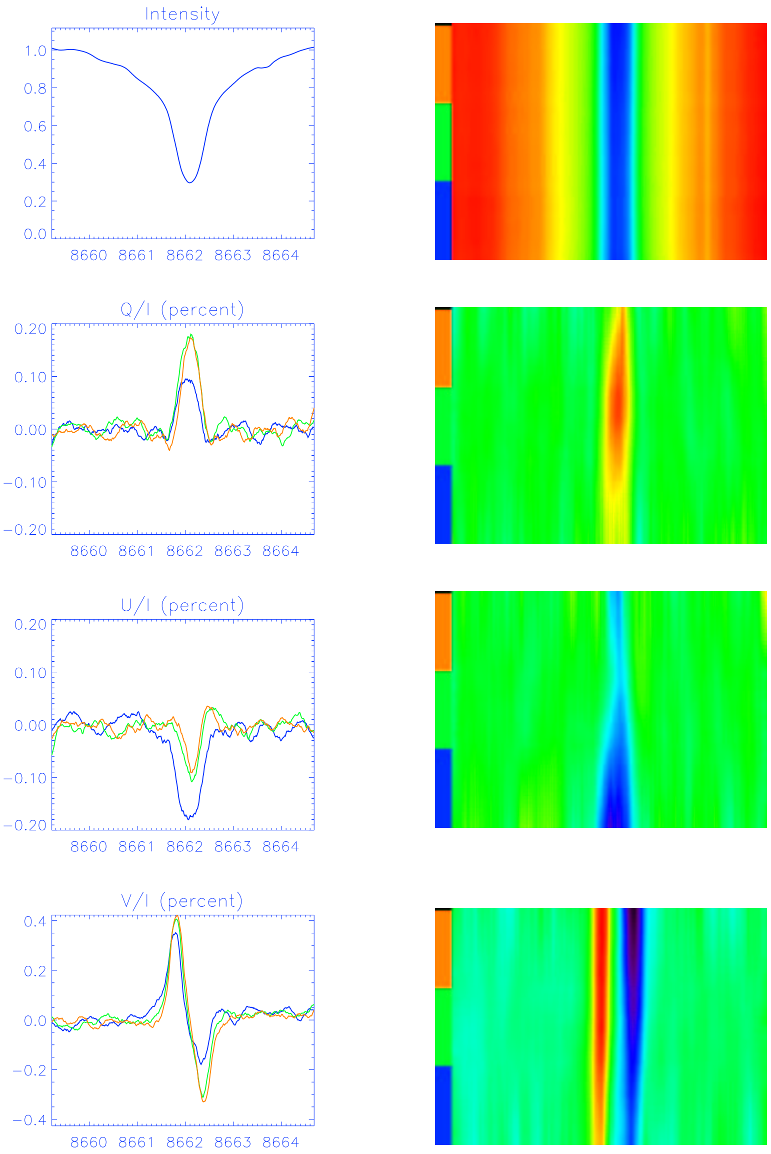

Figure 3. The full Stokes vector of the 8662 Å line of Ca II observed on the solar disk at about $5''$ from the limb during the equinox period of September 2000. The positive reference direction for Stokes Q is along the line perpendicular to the radial direction through the observed point. Each of the three curves for the fractional polarization shows the result of the spatial average performed along the corresponding coloured portion of the spectrograph's slit. This spectropolarimetric observation with the Tenerife Gregory Coudé Telescope (GCT) is the result of an ongoing collaboration between Dittmann, Semel and Trujillo Bueno.

of Fig. 3). This mechanism is called *dichroism* in a weakly magnetized medium (see Trujillo Bueno and Landi Degl'Innocenti, 1997), and plays a key role in producing the observed "enigmatic" linear polarization signals in a variety of chromospheric lines (Trujillo Bueno, 1999; 2001; Manso Sainz & Trujillo Bueno, 2001; Trujillo Bueno & Manso Sainz, 2001; Trujillo Bueno et al., 2001*b*).

4. Remote Sensing of Chromospheric Magnetic Fields via the Hanle and Zeeman Effects

The physical interpretation of weak polarization signals requires to calculate the polarization of the atomic or molecular levels within the framework of a rigorous theory for the generation and transfer of polarized radiation. A suitable theory for many spectral lines of diagnostic interest is the density matrix polarization transfer theory of Landi Degl'Innocenti (1982; 1983).

The issue of the Hanle effect in the Ca II IR triplet has been investigated in detail by Manso Sainz & Trujillo Bueno, who have developed a general multilevel scattering polarization code taking into account the Hanle and Zeeman effects. The results of some applications have been advanced in some workshop presentations (Manso Sainz & Trujillo Bueno, 2001; Trujillo Bueno & Manso Sainz, 2001). Firstly, we considered the zero magnetic field reference case and demonstrated that the "enigmatic" relative Q/I amplitudes (among the three lines) observed by Stenflo et al. (2000) are the natural consequence of the existence of a sizable amount of atomic polarization in the metastable levels $^2\mathrm{D}_{3/2}$ and $^2\mathrm{D}_{5/2}$ (which are the lower-levels of the Ca II IR triplet). Secondly, we have investigated the Hanle effect in the IR triplet at 8498, 8542 and 8662 Å considering a realistic multilevel atomic model. Fig. 4 is one of our most recent and interesting results, which we will describe in full detail in forthcoming publications. It shows the fractional linear polarization calculated at $\mu = 0.1$ (about $5''$ from the limb) assuming magnetic fields of given inclination, but with a random azimuthal component within the spatio-temporal resolution element of the observation.

The results of this figure indicate that, basically, there are two possible magnetic-field topologies (assuming that the magnetic field lines have a random azimuthal component over the spatio-temporal resolution element of the observations) for which the limb polarization signals of the 8542 and 8662 Å lines can have amplitudes with $Q/I \gtrsim 0.1\%$ (i.e. of the order of the observed ones). As one could have expected, the first topology corresponds to magnetic fields with inclinations $\theta_B \lesssim 30°$. The second corresponds to magnetic fields which are practically parallel to the solar surface, i.e. "horizontal" fields with $80° \lesssim \theta_B \lesssim 100°$. This demonstrates that a significant amount of the atomic polarization that is induced by optical pumping processes in the metastable $^2\mathrm{D}_{3/2}$ lower-level survives the partial Hanle-effect destruction produced by canopy-like horizontal fields with intensities in the gauss range, and generates very significant linear polarization signals via the dichroism mechanism.

Our spectropolarimetric observation of Fig. 3 is only one example among many other different cases of our GCT observations. The sizable Stokes V/I signal of Fig. 3 indicates that we were observing here a moderately magnetized

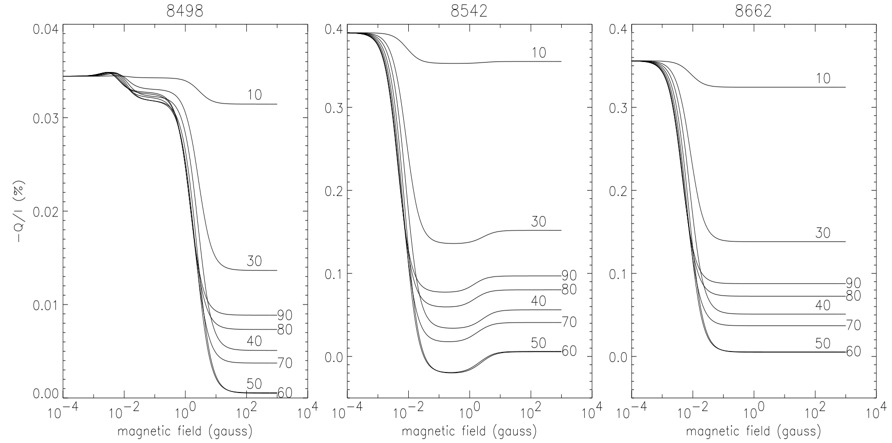

Figure 4. The fractional linear polarization of the Ca II IR triplet calculated at $\mu = 0.1$ (about $5''$ from the limb) in an isothermal atmosphere with T=6000 K. Each curve corresponds to the indicated inclination (θ_B) of the assumed random-azimuth magnetic field.

region close to the solar limb. Within the framework of Landi Degl'Innocenti's (1983) density matrix theory, this particular observation of Fig. 3 cannot be modelled assuming a random azimuth magnetic field, otherwise Stokes U would have been undetectable. It would be of interest to confirm with other telescopes our detection of that significant U/I signal for the 8662 Å Ca II line, because it can only be due to the existence of quantum interferences (coherences!) among the Zeeman sublevels of the metastable $^2\mathrm{D}_{3/2}$ lower-level (see Trujillo Bueno, 2001; Section 7). For this particular observation of Fig. 3 a good fit can be obtained assuming deterministic magnetic fields with intensities in the gauss range and having inclinations $\theta_B \lesssim 30°$ (see the Hanle and Zeeman radiative transfer multilevel modeling of Fig. 5). In any case, we observed also more "quiet" and more "active" solar limb regions. In some regions we detect Q, but $U{\approx}0$ and/or $V{\approx}0$. In other regions we detect V, but $Q{\approx}U{\approx}0$. The physical interpretation of these spectropolarimetric observations in terms of the Hanle and Zeeman effects is giving us valuable clues about the intensities and magnetic field topologies in different regions of the solar chromosphere.

5. Concluding Remarks

The physical origin of the "enigmatic" linear polarization signals observed in a variety of chromospheric lines is the existence of atomic polarization in their metastable lower-levels, which permits the operation of a *dichroism* mechanism that has nothing to do with the transverse Zeeman effect. Therefore, the absorption process itself plays a key role in producing the linear polarization signals observed in the "quiet" solar chromosphere as well as in solar filaments.

The population imbalances and coherences among the Zeeman sublevels of such *long-lived* atomic levels can survive sufficiently in the presence of horizontal

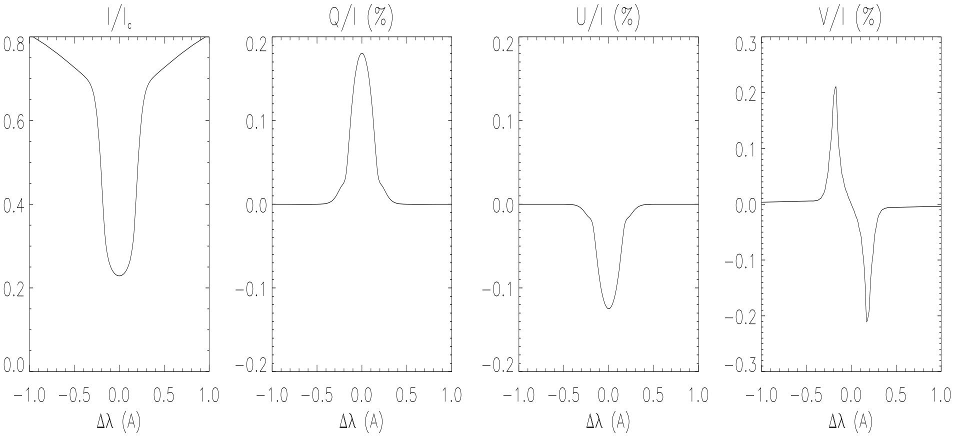

Figure 5. The emergent Stokes parameters of the Ca II 8662 Å line calculated at $\mu = 0.1$ in the FAL-C semi-empirical model. We have assumed a deterministic magnetic field of 20 gauss that is inclined by 25° with respect to the radial direction. This figure is to be compared with the observational results of Fig. 3.

magnetic fields having intensities in the gauss range. Therefore, in general, one should not feel obliged to conclude that the magnetic fields of the "quiet" solar chromosphere have to be either extremely low (i.e. with intensities $B \lesssim 10$ mG), or, alternatively, oriented preferentially along the radial direction. The physical interpretation of our spectropolarimetric observations of chromospheric lines in terms of the Hanle and Zeeman effects indicates that the magnetic field topology can be considerably more complex, having *both* moderately inclined and practically horizontal field lines. A physically plausible scenario that might lead to polarization signals in agreement with the observations is that resulting from the superposition of miriads of different loops of magnetic field lines connecting opposite polarities. This suggested magnetic field topology is somehow reminiscent of the magnetic structure model of the "quiet" transition region proposed by Dowdy et al. (1986), but scaled down to the spatial dimensions of the solar chromosphere.

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