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Radiative transfer modeling of the Hanle effect in convective atmospheres

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Abstract. This paper summarizes the results of a recent investigation on the Hanle effect in atomic and molecular lines, which indicates that there is a vast amount of "hidden" magnetic energy and (unsigned) magnetic flux in the internetwork regions of the quiet solar photosphere. This hidden magnetic energy, localized in the (intergranular) downflowing plasma of the solar photosphere, is carried mainly by tangled fields at sub-resolution scales with strengths between the equipartition field values and $\sim$1 kG, and is more than sufficient to compensate the radiative energy losses of the solar outer atmosphere.

Keywords. Sun: magnetic fields, Sun: atmosphere, polarization, scattering, convection, line: formation, radiative transfer, stars: magnetic fields

1. Introduction

Deciphering and understanding the small-scale magnetic activity of the "quiet" solar photosphere should help to solve many of the key problems of solar and stellar physics, such as the magnetic coupling to the outer atmosphere and the coronal heating (e.g., Priest 2006). Unfortunately, the Zeeman effect polarization as a diagnostic tool is "blind" to magnetic fields that are tangled on scales too small to be resolved. For this reason, it is currently believed that, via Zeeman effect diagnostics with the available instrumentation, we are seeing only the "tip of the iceberg" of solar surface magnetism (e.g., Stenflo 1994; Cattaneo 1999; Sánchez Almeida *et al.* 2003). This fact highlights the need to develop a reliable way to investigate how much magnetic flux remains hidden from view.

In order to investigate the magnetism of the solar photospheric regions that look empty in solar magnetograms we have carried out a detailed theoretical analysis of observations of scattering polarization in atomic and molecular lines (see Trujillo Bueno 2003*a*; Shchukina & Trujillo Bueno 2003; Trujillo Bueno *et al.* 2004; Asensio Ramos & Trujillo Bueno 2005). Our interpretations of the linear polarization amplitudes observed in the Sr I 4607 Å line and in MgH lines are based on three-dimensional (3D) radiative transfer modeling in snapshots taken from the hydrodynamical simulations of solar surface convection by Asplund *et al.* (2000). Our analysis of the observed scattering polarization in C_2 lines is based on the application of our Hanle-effect line-ratio technique. A detailed review including our arguments against collisional depolarization in the observed C_2 lines, but in favour of a significant collisional depolarization in MgH lines, can be found in Trujillo Bueno *et al.* (2006).

2. Scattering physics and the Hanle effect

In order to highlight the diagnostic potential of the Hanle effect, let us consider the 90° scattering case for a $J_l = 0 \rightarrow J_u = 1$ line transition, in the absence and in the presence of

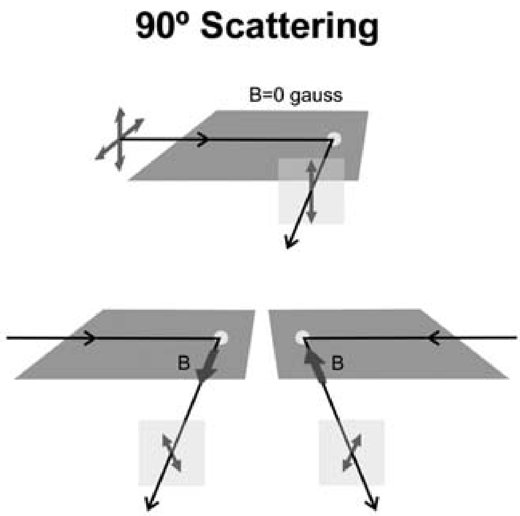

Figure 1. The 90° scattering case in the absence (top panel) and in the presence (bottom panels) of a magnetic field.

a magnetic field (see Fig. 1). For this type of transition and geometry the largest polarization amplitude occurs for the zero field reference case, with the direction of the linear polarization as indicated in the top panel (i.e, perpendicular to the scattering plane). The two lower panels of Fig. 1 illustrate what happens when the scattering processes take place in the presence of a magnetic field pointing (a) towards the observer (left panel) or (b) away from him/her (right panel). In both situations the polarization amplitude is reduced with respect to the previously discussed unmagnetized case. Moreover, the direction of the linear polarization is rotated with respect to the zero field case. Typically, this rotation is counterclockwise for case (a), but clockwise for case (b)†. Therefore, when opposite magnetic polarities coexist within the spatio-temporal resolution element of the observation the direction of the linear polarization is like in the top panel of Fig. 1, simply because the rotation effect cancels out. However, the polarization amplitude is indeed reduced with respect to the zero field reference case, which provides an "observable" that can be used for obtaining empirical information on hidden, mixed polarity fields at subresolution scales in the solar atmosphere (Stenflo 1994; Trujillo Bueno *et al.* 2004).

The basic formula of the Hanle effect results from equating the Zeeman splitting of the upper level of the spectral line under consideration with the level's natural width:

$$B_H \approx 1.137 \times 10^{-7} / (t_{\rm life}\, g_L), \tag{2.1}$$

where $t_{\rm life} \approx 1/A_{ul}$ (being A_{ul} the Einstein coefficient for the spontaneous emission process) is the level's lifetime (in seconds) and g_L its Landé factor. This expression allows us to estimate the critical magnetic field strength B_H (in G) for which one may expect a sizable change of the scattering polarization signal with respect to the unmagnetized reference case (e.g., $B_H \approx 23$ G for the Sr I line at 4607 Å and $B_{\rm H} \approx 8$ G for the C_2 5161.84 Å line). This formula provides a reliable estimation when radiative transitions dominate the atomic excitation.

† This occurs when the Landé factor, g_L, of the transition's upper level is positive, while the opposite behavior takes place if $g_L < 0$.

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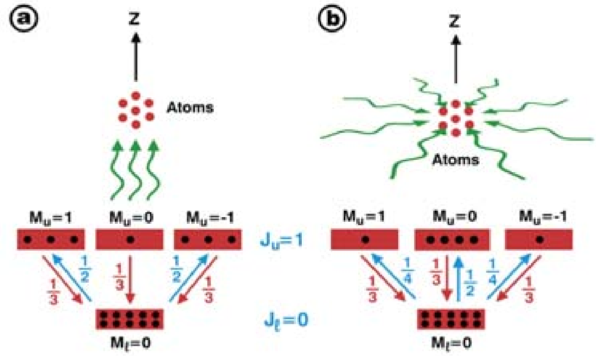

Figure 2. Illustration of the atomic polarization that is induced in the upper level of a two-level atom (with $J_l = 0$ and $J_u = 1$) by two types of anisotropic illuminations (i.e., vertical illumination in case **a** and horizontal illumination in case **b**). The incident radiation field is assumed to be unpolarized and with axial symmetry around the vertical direction, which is our choice here for the quantization axis of total angular momentum. Note that the alignment coefficient of the upper level (i.e. $\rho^2_0 = (N_1 - 2N_0 + N_{-1})/\sqrt{6}$, N_i being the populations of the magnetic sublevels) is positive in case (**a**) (where the incident beam is parallel to the quantization axis), but negative in case (**b**) (where the incident beams are perpendicular to the quantization axis).

Which is the true physical origin of this so-called scattering line polarization? Obviously, if there is no Zeeman splitting there is no wavelength shift between the π and σ transitions. Accordingly, one might think that there is no measurable polarization because the polarizations of such components cancel out. However, it is easy to see that this is only true if the populations of the individual magnetic sublevels pertaining to the lower and/or upper level of the spectral line under consideration are assumed to be identical. To this end, consider the case of a line transition with $J_l = 0$ and $J_u = 1$ and choose the quantization axis of total angular momentum along the solar radius vector through the observed point. Assume that the population of the upper-level magnetic sublevel with $M_u = 0$ is smaller than the populations of the magnetic sublevels with $M_u = \pm 1$. As a result, even in the absence of a magnetic field (zero Zeeman splitting), we can have a non-zero linear polarization signal, simply because the number of σ transitions, per unit volume and time, will be larger than the number of π transitions.

What is the key physical mechanism that induces atomic level polarization? The answer lies in *the anisotropic illumination of the atoms*. This is easy to understand by considering the academic case of a unidirectional unpolarized light beam that illuminates a gas of two-level atoms with $J_l = 0$ and $J_u = 1$ and that is propagating along the direction chosen as the quantization axis of the total angular momentum (see left panel of Fig. 2). Since these atoms can only absorb ± 1 units of angular momentum from the light beam, only transitions corresponding to $\Delta M = \pm 1$ are effective, so that no transitions occur to the $M = 0$ sublevel of the upper level. Thus, when radiative transitions dominate the atomic excitation, the upper-level sublevels with $M = 1$ and $M = -1$ would be more populated than the $M = 0$ sublevel. Interestingly, if the radiative illumination is *horizontal* instead of vertical –that is, with the unpolarized light beams forming an angle of 90° with the quantization axis, then the upper-level sublevels with $M = 1$ and $M = -1$ would be less populated than the $M = 0$ sublevel (see right panel of Fig. 2).

Is the above-mentioned type of anisotropic pumping taking place in the atmospheres of the Sun and of other stars? Figure 3 illustrates the typical anisotropic illumination that we have in the outer layers of a stellar atmosphere, showing that the outgoing radiation is predominantly *vertical* (case a of Fig. 2) while the incoming radiation predominantly

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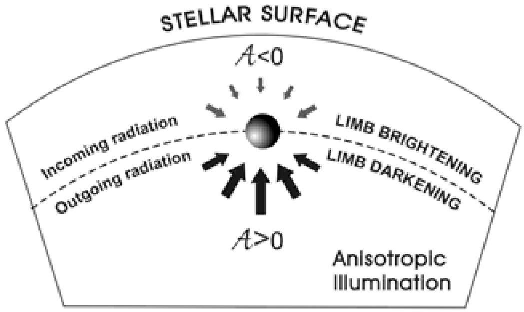

Figure 3. Anisotropic illumination of the outer layers of a stellar atmosphere, indicating that the (mainly vertical) outgoing radiation shows limb darkening while the (mainly horizontal) incoming radiation shows limb brightening. The "degree of anisotropy" of the incident radiation field is quantified by $\mathcal{A} = \bar{J}^2_0/\bar{J}^0_0$, where $\bar{J}^0_0$ is the familiar frequency-weighted mean intensity and $\bar{J}^2_0 \approx \int d\nu \oint \phi_\nu \frac{d\vec{\Omega}}{4\pi} \frac{1}{2\sqrt{2}}(3\mu^2 - 1)I_{\nu,\vec{\Omega}}$ (with ϕ_ν the absorption line shape and $I_{\nu,\vec{\Omega}}$ the Stokes-I parameter as a function of frequency ν and direction $\vec{\Omega}$, while $\mu = \cos\theta$, with θ the polar angle with respect to the local vertical direction). The possible values of the anisotropy factor $\mathrm{W} = \sqrt{2}\,\mathcal{A}$ vary between $\mathrm{W} = -1/2$, for the limiting case of illumination by a purely horizontal radiation field without any azimuthal dependence (case b of Fig. 2), and $\mathrm{W} = 1$ for purely vertical illumination (case a of Fig. 2). It is important to point out that the larger the anisotropy factor the larger the fractional atomic polarization that can be induced, and the larger the amplitude of the emergent linear polarization.

horizontal (case b of Fig. 2). It is also very important to point out that the "degree of anisotropy" of the radiation field within a stellar atmosphere is very sensitive to the source-function gradient (see Fig. 4 in Trujillo Bueno 2001). The larger the gradient the greater the anisotropy of the pumping radiation field, and the larger the amount of atomic level polarization. Therefore, at a given height in the inhomogeneous solar photosphere, the "degree of anisotropy" of the solar continuum radiation in the (granular) upflowing regions is significantly larger than in the (intergranular) downflowing plasma (see Fig. 4 in Trujillo Bueno 2003*a*).

3. Radiative transfer modeling in convective atmospheres

In general, the physical interpretation of spectral line polarization requires calculating, for multilevel systems, the population and polarization of each atomic level that is consistent with both the intensity and polarization of the radiation field generated within the (generally magnetized) plasma under consideration. This is a very involved *non-local* and *non-linear* radiative transfer (RT) problem which requires solving the rate equations for the elements of the atomic density matrix and the Stokes-vector transfer equation for each of the allowed transitions in the chosen multilevel model (e.g., Trujillo Bueno 2003*b*). Once such a selfconsistent excitation state is known along the line of sight, it is then straightforward to solve the transfer equation in order to obtain the emergent Stokes profiles to be compared with spectropolarimetric observations.

We have carried out this type of detailed radiative transfer calculations in a 3D photospheric model resulting from Asplund *et al.*'s (2000) hydrodynamical simulations of solar surface convection (see Shchukina & Trujillo Bueno 2003; Trujillo Bueno *et al.* 2004; Asensio Ramos & Trujillo Bueno 2005). In order to simply highlight the basic physics and the key point of our Hanle-effect diagnostic method, it suffices to mention that for the case of the Sr I line at 4607 Å the following approximate expression can be used to

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estimate the emergent fractional linear polarization at the line center (Trujillo Bueno 2003*b*):

$$Q/I \approx \frac{3}{2\sqrt{2}}(1-\mu^2)\,\frac{\mathcal{H}}{1+\delta_u}\,\mathcal{A}, \tag{3.1}$$

where $\mathcal{A} = \bar{J}^2_0/\bar{J}^0_0$ is the "degree of anisotropy" of the line radiation, δ_u is the collisional depolarizing rate of the upper-level in units of A_{ul}, and $\mathcal{H}$ is the Hanle depolarization factor of the assumed *microturbulent* and *volume filling* field which varies between $\mathcal{H} = 1$ for $B = 0\,$G and $\mathcal{H} = 1/5$ for $B > 200\,$G. In Eq. (3.1) $\mathcal{A}$, $\mathcal{H}$ and δ_u have to be evaluated at the atmospheric height where the line center optical depth is unity along the line of sight specified by $\mu = \cos\theta$ (with θ the heliocentric angle). The observable is Q/I at several μ positions on the solar disk and we want to determine the strength of the hidden field, which is contained in $\mathcal{H}$. Obviously, this Hanle-effect diagnostics will be reliable only if one has a very good knowledge of δ_u and of $\mathcal{A}$. We use realistic δ_u-values (Faurobert-Scholl *et al.* 1995), which turn out to be the largest rates among those found in the literature. In order to obtain an accurate determination of $\mathcal{A}$ it is crucial to use a realistic 3D model of the "quiet" solar photosphere.

4. The Hanle effect in the Sr I 4607 Å line

In order to achieve a reliable Hanle-effect diagnostics with the photospheric line of Sr I at 4607 Å, Trujillo Bueno *et al.* (2004) used snapshots from Asplund *et al.*'s (2000) solar surface convection simulations, which are very convincing because non-LTE spectral synthesis of a multitude of iron lines shows remarkable agreement with the observed spectral line profiles (e.g., Shchukina & Trujillo Bueno 2001). We found that the spatially and temporally averaged emergent Stokes profiles for $B = 0\,$G give a Q/I that is substantially larger than observed, thus indicating the need for invoking magnetic depolarization.

It is obvious that with a single spectral line we do not have enough information to constrain the shape of the Probability Distribution Function, PDF(B), describing the fraction of quiet Sun occupied by magnetic fields with strength B. For this reason, we chose the functional form of the PDF. The key point, however, is to be conservative in the choice of the functional form of the PDF, in order to avoid exaggerating the resulting mean strength of the hidden field. For this reason, Trujillo Bueno *et al.* (2004) presented results only for the two forms: (a) $\mathrm{PDF}(B) = \delta(B - \langle B\rangle)$ and (b) $\mathrm{PDF}(B) = \mathrm{e}^{-B/\langle B\rangle}/\langle B\rangle$, where $\langle B\rangle$ is the mean field strength. Obviously, option (a) seriously underestimates $\langle B\rangle$, while option (b) provides a much more realistic estimation.

As shown in Fig. 4, for the standard case (a) of a single value microturbulent field we find that $\langle B\rangle \approx 60\,$G leads to a notable agreement with the observed Q/I. Note that the strength of the hidden field required to explain the Q/I observations seems to decrease with height in the atmosphere, from the 70 G needed to explain the observations at $\mu = 0.6$ to the 50 G required to fit the observations at $\mu = 0.1$. This corresponds to an approximate height range between 200 and 400 km above the solar visible "surface".

Concerning the case of an exponential PDF, we see in Fig. 4 that $\langle B\rangle \approx 130\,$G yields a fairly good fit to the observed fractional linear polarization. In this more realistic case $E_{\mathrm{m}} = \langle B^2\rangle/8\pi \approx 1300\,\mathrm{erg\,cm^{-3}}$ (i.e., $\langle B^2\rangle^{1/2} \approx 180\,$G), which is about 20% of the kinetic energy density produced by convective motions at a height of 200 km in the 3D photospheric model. As pointed out by Trujillo Bueno *et al.* (2004), for this case the total magnetic energy stored in the internetwork regions turns out to be larger than that corresponding to the kG fields of the network patches.

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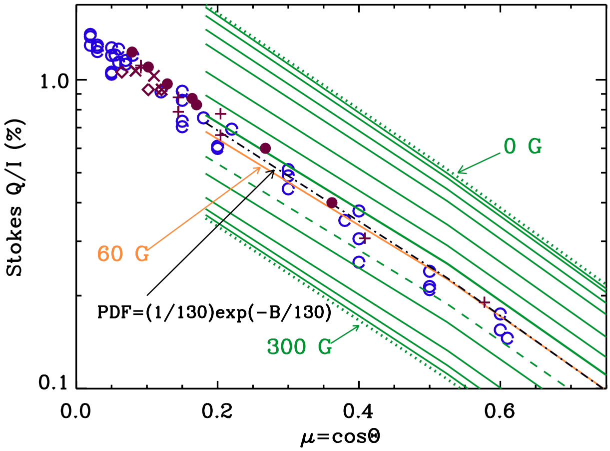

Figure 4. Center-to-limb variation of the fractional linear polarization in the center of the Sr I 4607 Å line after subtraction of the continuum polarization. The various symbols correspond to observations from different authors (see Trujillo Bueno *et al.* 2004, for details). (○) various observations taken during a minimum of the solar cycle. The remaining symbols correspond to observations taken during the most recent maximum of the solar cycle. Colored (or solid, dashed, and dotted) lines show the results of our 3D scattering polarization calculations in the presence of a volume-filling and single value microturbulent field (from top to bottom: 0, 5, 10, 15, 20, 30, 40, 50, 60, 80, 100, 150, 200, 250 and 300 G). Note that the best average fit to the observations is obtained for 60 G. The black, dashed-dotted line indicates the resulting Q/I amplitudes for the case of a microturbulent field described by an exponential Probability Distribution Function with $\langle B \rangle = 130$ G. (From Trujillo Bueno *et al.* 2004).

5. The Hanle effect in C_2 lines

It has been pointed out recently that the observed scattering polarization in very weak spectral lines, such as those observed by Stenflo & Keller (1997) and Gandorfer (2000) in MgH and C_2, is coming mainly from the (granular) upflowing regions of the solar photosphere (Trujillo Bueno 2003*a*; Trujillo Bueno *et al.* 2004). Therefore, the Hanle effect in such molecular lines can be used to obtain information on unresolved magnetic fields in the granular regions of solar surface convection. To this end, a very powerful diagnostic tool is the Hanle-effect line-ratio technique for the C_2 lines of the Swan system (see the recent review by Trujillo Bueno *et al.* 2006). The advantage of this technique is that one does not need to carry out radiative transfer modeling of the observed molecular scattering polarization, given that the strength of the hidden field can be simply obtained through a direct comparison between the linear polarization amplitude observed in the selected $R_2(J)$ ($P_2(J)$) line and that observed in the $R_3(J-1)$ ($P_3(J-1)$) line.

As seen in Fig. 7 of Trujillo Bueno *et al.* (2006) this type of analysis of the Hanle effect in the C_2 lines of the Swan system also supports the hypothesis of a hidden magnetic field at sub-resolution scales. However it suggests a mean field strength $\langle B \rangle \sim 10$ G, which is much smaller than what is needed to explain the observations of the Sr I 4607 Å line presented earlier, which point instead to a hidden field with $\langle B \rangle \sim 100$ G. A resolution of this "enigma" was found when it was pointed out by Trujillo Bueno (2003*a*) that the observed scattering polarization in very weak spectral lines, such as those of C_2 and MgH, is coming mainly from the upflowing regions of the quiet solar photosphere (see also Fig. 2 of Trujillo Bueno *et al.* 2004), which implies that $\langle B \rangle \sim 10$ G corresponds mainly to the granular regions. Therefore, we now must ask how large the strength of the hidden field in the (intergranular) downflowing regions has to be, in order to be able to explain the

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inferred depolarization in the Sr I 4607 Å line. Interestingly, we find that the distribution of magnetic field strengths in the (intergranular) downflowing regions of the quiet solar photosphere must produce saturation for the Hanle effect in the Sr I 4607 Å line formed there. As seen in Fig. 4, saturation *for the simplest case of a single value microturbulent field* occurs for $B \gtrsim 200$ G. For this reason, Trujillo Bueno *et al.* (2004) concluded that their joint analysis of the Hanle effect in C_2 lines and in the Sr I 4607 Å line suggests that the strength of the hidden magnetic field "fluctuates" on the spatial scales of the solar granulation pattern, with weak fields ($\langle B \rangle \sim 10$ G) in the (granular) upflowing regions and much stronger fields in the (intergranular) downflowing plasma. Trujillo Bueno *et al.* (2006) explain in some detail the arguments that led them to conclude that most of the ensuing magnetic energy is actually carried by tangled magnetic fields at sub-resolution scales with strengths between the equipartition field values and ~1 kG.

6. Concluding remarks

Taking into account that at any given time during the solar magnetic activity cycle most of the solar surface is covered by the quiet internetwork regions, it is clear that the results of our analysis of the scattering polarization observed in the Sr I 4607 Å line and in C_2 lines might have far-reaching implications in solar and stellar physics.

The hot outer regions of the solar atmosphere (chromosphere and corona) radiate and expand, which takes up energy. By far the largest energy losses stem from chromospheric radiation, with a total energy flux of $\sim 10^7$ erg cm^{-2} s^{-1} (Anderson & Athay 1989). The magnetic energy density corresponding to our simplest model with $\langle B \rangle \approx 60$ G is 140 erg cm^{-3}, which leads to an energy flux comparable to the chromospheric energy losses, when using either the typical value of ~1 km s^{-1} for the convective velocity, or the Alfvén speed, $v_A = B/(4\pi\rho)^{1/2}$, where ρ is the gas density. In reality, as pointed out above, the true magnetic energy density that is stored in the quiet solar photosphere at any given time during the solar cycle is very much larger than 140 erg cm^{-3}. For example, the magnetic energy density corresponding to the (still conservative) case of an exponential distribution of field strengths with $\langle B \rangle \approx 130$ G is 1300 erg cm^{-3}, which implies an energy flux 10 times larger than the chromospheric radiative energy losses. Only a relatively small fraction would thus suffice to balance the energy losses of the solar outer atmosphere. In conclusion, the "hidden" magnetic field inferred by Trujillo Bueno *et al.* (2004) could thus provide the clue to understanding how the solar chromosphere and corona are heated.

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Discussion

R. Stein: Our magneto-convection simulations show that the weak fields are swept out of the upflows and concentrated at the edges of the intergranular lanes.

J. Trujillo Bueno: Our joint theoretical analysis of observations of the Hanle effect in the Sr I 4607 Å line and in C_2 lines reveals that the hidden magnetic field fluctuates on the spatial scales of the solar granulation pattern, with relatively weak fields in the (granular) upflowing regions and much stronger tangled fields in the (intergranular) downflowing plasma. The inferred mean field strength is of the order of 100 G –that is, significantly larger than the values you have used in Stein & Nordlund (2006).

A. S. Brun: Since the magnetic field is a vector, only the radial component of **B** is swept by the convective eddies to the downflow network, not the horizontal component of **B**. How does this distinction between B_σ and B_μ modify your result on the average field strength $\langle B \rangle$?

J. Trujillo Bueno: I would say instead that magneto-convection modifies both the intensity and orientation of the magnetic field vector. It is important to emphasize that our estimation of $\langle B \rangle$ is based on the microturbulent field model, which assumes that we have all possible magnetic field orientations below the mean-free-path of the *line-core* photons. This is probably a reliable approximation for estimating $\langle B \rangle$ because in "quiet" regions the observed Stokes U profiles are negligible compared with Stokes Q. On the other hand, the magnetic field of magneto-convection simulations seems to be indeed pretty chaotic within the spatio-temporal resolution element of the spectropolarimetric observations. We are now investigating the Hanle depolarization produced by the actual magnetic fields that we have in snapshots of magneto-convection simulations. Each snapshot is characterized by a given $\langle B \rangle$ value, and our aim is to determine which one leads to the best agreement with the observed scattering polarization signals. For the moment, information on the depolarization produced by microturbulent fields of given inclination but with a random azimuth can be found in Fig. 4 of Trujillo Bueno *et al.* (2006).