

Spectropolarimetric diagnostics of unresolved magnetic fields in the quiet solar photosphere

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Abstract. A few years before the Hinode space telescope was launched, an investigation based on the Hanle effect in atomic and molecular lines indicated that the bulk of the quiet solar photosphere is significantly magnetized, due to the ubiquitous presence of an unresolved magnetic field with an average strength $\langle B \rangle \approx 130$ G. It was pointed out also that this “hidden” field must be much stronger in the intergranular regions of solar surface convection than in the granular regions, and it was suggested that this unresolved magnetic field could perhaps provide the clue for understanding how the outer solar atmosphere is energized. In fact, the ensuing magnetic energy density is so significant that the energy flux estimated using the typical value of 1 km/s for the convective velocity (thinking in rising magnetic loops) or the Alfvén speed (thinking in Alfvén waves generated by magnetic reconnection) turns out to be substantially larger than that required to balance the chromospheric energy losses. Here we present a brief review of the research that led to such conclusions, with emphasis on a new three-dimensional radiative transfer investigation aimed at determining the magnetization of the quiet Sun photosphere from the Hanle effect in the Sr I 4607 Å line and the Zeeman effect in Fe I lines.

Keywords. Sun: magnetic fields, Sun: atmosphere, polarization, scattering, radiative transfer, stars: atmospheres

1. Introduction

The subject of this paper is small-scale (SS) magnetic fields in the quiet solar photosphere. Most part of the solar surface is covered by the inter-network regions of the quiet Sun, which appear empty (i.e., devoid of magnetic signatures) in low resolution magnetograms. However, such regions are magnetized, as shown by the weak Stokes V signals (produced by the longitudinal Zeeman effect) that Livingston & Harvey (1971) could detect in the interiors of supergranular cells. Over the last 10 years, the complexity of the SS magnetic fields of the quiet solar photosphere has been studied vigorously through high-spatial resolution observations of the polarization produced by the Zeeman effect in Fe I lines, using both ground-based telescopes (e.g., Domínguez Cerdeña *et al.* 2003; Khomenko *et al.* 2003; Lites & Socas-Navarro 2004; Domínguez Cerdeña *et al.* 2006; Harvey *et al.* 2007; Martínez González *et al.* 2007), the HINODE space telescope (e.g., Centeno *et al.* 2007; Orozco Suárez *et al.* 2007; Rezaei *et al.* 2007; Lites *et al.* 2008; Ishikawa & Tsuneta 2009; Asensio Ramos 2009; Martínez González *et al.* 2010; Danilovic *et al.* 2010; Martínez Pillet *et al.* 2011a; Viticchié & Sánchez Almeida 2011; Manso Sainz *et al.* 2011), and the balloon-borne telescope SUNRISE (e.g., Solanki *et al.* 2010; Borrero *et al.* 2010; Lagg *et al.* 2010; Martínez González *et al.* 2012).

Diagnostic tools based on the polarization of the Zeeman effect are however practically blind to the presence of magnetic fields that are randomly oriented on scales too small to be resolved. Therefore, non-detection of Zeeman polarization does not necessarily imply absence of magnetic fields.

A key question is: how significant is the degree of magnetization of the plasma of the quiet Sun? To answer this question it is necessary to investigate how much magnetic flux and energy reside at small (unresolved) scales. To explore this “hidden” magnetism of the quiet Sun one has to apply diagnostic techniques based on the Hanle effect in atomic and molecular lines, ideally complementing them with those based on the Zeeman effect (see the review by Trujillo Bueno *et al.* 2006). In this paper we provide a brief summary of the research carried out over the last few years, with emphasis on three-dimensional radiative transfer investigations of the Hanle effect in the Sr I line at 4607 Å and of the Zeeman effect in some Fe I lines.

2. Polarization in Spectral Lines

The most powerful tool for the diagnostics of magnetic fields in the atmospheres of the Sun and of other stars is the interpretation of spectropolarimetric observations (e.g., Landi Degl’Innocenti & Landolfi 2004). Polarization in spectral lines can be induced and modified by several physical mechanisms. In the quiet Sun the most important ones are the Zeeman effect (Zeeman 1897), anisotropic radiation pumping (Kastler 1950), and the Hanle effect (Hanle 1924).

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 ($\Delta M = M_u - M_l = 0$), σ_{blue} ($\Delta M = +1$) and σ_{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 V/I amplitude that for not too strong fields scales with the ratio, R , between the Zeeman splitting $\Delta\lambda_B$ and the Doppler line-width $\Delta\lambda_D$:

$$V/I \sim R = \frac{\Delta\lambda_B}{\Delta\lambda_D} \sim \frac{\lambda B}{\sqrt{T/\alpha}} \ll 1, \quad (2.1)$$

with α the atomic weight of the atom under consideration. The Stokes V signal changes its sign for opposite orientations of the magnetic field vector. This so-called *longitudinal Zeeman effect* responds to the line-of-sight component of the magnetic field (B_{\parallel}). On the contrary, the *transverse Zeeman effect* responds to the component of the magnetic field perpendicular to the line of sight (B_{\perp}), producing instead linear polarization signals quantified by the Stokes Q and U parameters. The Zeeman polarization Q/I and U/I amplitudes are approximately proportional to R^2 :

$$Q/I \ \& \ U/I \sim R^2. \quad (2.2)$$

Taking into account that in the quiet Sun $R \ll 1$, the Stokes Q/I and U/I signals of solar spectral lines are normally negligible for intrinsically weak fields (typically $B \lesssim 100$ G). As a result, Zeeman linear polarization turns out to be often below the noise level of present observational possibilities. It is also important to note that if only a fraction, f , of the observational resolution element is filled with magnetic field, then B_{\parallel} (inferred from V) scales with f , while B_{\perp} (inferred from Q and U) scales with \sqrt{f} (cf., Landi Degl’Innocenti & Landolfi 2004).

Anisotropic radiation pumping. The spectral line polarization that is induced by scattering processes in stellar atmospheres is directly related with the anisotropic illumination of the atoms. The presence of a magnetic field is not necessary for producing such a polarization. The absorption of anisotropic radiation produces atomic level polarization (i. e., population imbalances and/or quantum coherence 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. 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. Such anisotropic radiation pumping processes are particularly efficient in creating atomic polarization if the depolarizing rates caused by elastic collisions are sufficiently low.

The Hanle effect is the modification of the atomic level polarization and of its ensuing observable effects on the emergent Stokes Q and U profiles. It is caused by the action of a magnetic field such that the corresponding Zeeman splitting is comparable to the inverse lifetime, t_{life} , of the degenerate atomic level under consideration (the upper or lower level of the chosen line transition). For the Hanle effect to operate, the magnetic field vector has to be inclined with respect to the symmetry axis of the pumping radiation field. Typically (but not always), the changes in the Stokes Q and U profiles due to the Hanle effect consist in a net depolarization and a rotation of the direction of linear polarization. If the azimuth of the magnetic field is uniformly distributed within the resolution element of the observation, rotations of the direction of linear polarization cancel out, but the reduction of the scattering polarization amplitude with respect to the zero-field case remains. Therefore, the Hanle effect has the diagnostic potential for detecting tangled magnetic fields on subresolution scales in the solar atmosphere. Fortunately, scattering processes in the solar atmosphere produce a rich linearly-polarized spectrum (Stenflo & Keller 1997).

3. Diagnostics of Zeeman-Effect Polarization

Most of our present empirical knowledge on solar surface magnetism stems from the analysis of the spectral line polarization caused by the Zeeman effect. Diagnostic tools based on the Zeeman effect aim at determining the magnetic field strength, the magnetic flux, and the inclination of the magnetic field. The advantages and disadvantages of Stokes diagnostics based on the Zeeman effect have been repeatedly discussed in the literature. An attractive feature is the relative simplicity of the physics of the Zeeman effect. The mere detection of the signature of the Zeeman effect in the observed spectral line polarization can be directly interpreted as the presence of a magnetic field. Another good news for the polarization of the Zeeman effect as a diagnostic tool is the large number of methods developed to extract quantitative properties of the magnetic field (see, for example, the reviews by Solanki 1993 and Khomenko 2006). We can mention the magnetic line ratio technique (see Stenflo 1973; Solanki *et al.* 1992; and references therein), methods based on spectral synthesis in atmospheric models resulting from magnetoconvection simulations (see, for example, Khomenko *et al.* 2005; Shelyag *et al.* 2007; Danilovic *et al.* 2010, and references therein), methods based on exploiting the hyperfine structure of some atoms (López Ariste *et al.* 2002; Asensio Ramos *et al.* 2007), and various inversion methods (Skumanich & Lites 1987; Ruiz Cobo & del Toro Iniesta 1992; Sánchez Almeida 1997; Socas-Navarro *et al.* 2000).

Among the major shortcomings we should mention the following ones. First, the Zeeman polarization signals observed in the quiet Sun are very weak compared to those observed in active regions, so that quantitative diagnostics of the magnetic field properties are always challenged by the presence of the measurement noise (e.g., Asensio Ramos 2009). Second, the polarization of the Zeeman effect as a diagnostic tool is practically *blind* to magnetic fields that are randomly oriented on scales too small to be resolved. In other words, the Zeeman polarization signals tend to cancel out when averaging. This is exactly the situation in the internetwork regions of the quiet Sun, where the observed Stokes V signals show an intermittent pattern of positive and negative polarities at spatial scales as small as the diffraction limit of the telescope used. For this reason, one expects that Zeeman-polarization inferences of $\langle |B_{\parallel}| \rangle$ (the mean unsigned “vertical” magnetic flux density) depend on the spatial resolution of the observation. As it can be seen in figure 3 of Sánchez Almeida & Martínez González (2011), such unsigned flux density seems indeed to be larger at the close to 0.3 arcsec resolution of HINODE ($\langle |B_{\parallel}| \rangle \approx 10\text{G}$) than at the 1 arcsec resolution of some ground-based observations ($\langle |B_{\parallel}| \rangle \approx 3\text{G}$). Such a figure suggests that the average unsigned vertical magnetic flux density increases with increasing angular resolution (i.e., with decreasing size of the resolution element L), as expected for the case of polarization signals produced by the random association of equal independent structures with size l smaller than L (see Sánchez Almeida 2009). Such a tentative extrapolation predicts a magnetic flux density of 36 G or 181 G, depending on whether the intrinsic size l is 100 km or 20 km, respectively.

Unfortunately, there is a large scatter in the unsigned flux density values obtained from high spatial resolution Zeeman-polarization measurements taken with the HINODE satellite (spatial resolution of about 0.3 arcsec) and the IMAX instrument on board SUNRISE (spatial resolution of about 0.15 arcsec). The values reported so far do not seem to show the above-mentioned expected behavior (see Solanki *et al.* 2010; Martínez Pillet *et al.* 2011b; Sánchez Almeida & Martínez González 2011; Orozco Suárez & Bellot Rubio 2012, and more references therein). Sánchez Almeida & Martínez González (2011) argue that these apparent inconsistencies are mostly due to unaccounted biases in the applied diagnostic techniques.

Summarizing, we can conclude that using only the Zeeman polarization technique is not a very suitable strategy for investigating magnetic fields that have complex unresolved geometries. There is some evidence that the complexity of the SS fields of the quiet Sun is so considerable that with the present instrumentation Zeeman effect diagnostics allow us to detect only the tip of the iceberg of the quiet Sun magnetism. For example, a recent estimation by Pietarila Graham *et al.* (2009) predicts that $\sim 80\%$ of the Stokes- V signals existing in the surface dynamo simulations of Vögler & Schüssler (2007) would not be observable at the HINODE resolution of 0.3 arcsec (cf., Emonet & Cattaneo 2001; Sánchez Almeida *et al.* 2003). Fortunately, unresolved magnetic fields can be detected through the Hanle effect.

4. Diagnostics of Hanle-Effect Polarization

Since opposite polarity fields contribute with the same sign to the Hanle depolarization, the Hanle effect in suitably chosen spectral lines was correctly considered a potentially powerful tool to explore SS magnetic fields that are tangled on scales too small to be resolved (Stenflo 1982). Another important advantage of the Hanle effect as a diagnostic tool of the quiet Sun magnetism is that it is sensitive to much weaker magnetic fields than those that can be detected through the Zeeman effect (i.e., in the range from 10^{-3} G up to a few hundred gauss, depending on the line transition). The main disadvantage

is that magnetic fields stronger than the Hanle saturation limit remain virtually indistinguishable (e.g., in the case of the Sr I 4607 Å line, for magnetic strengths $B > 250$ G). Therefore, both plasma diagnostic tools are rather complementary.

A useful formula to estimate the magnetic field strength, B_c (measured in G), for the onset of the Hanle effect in a line transition without atomic polarization in its lower level (such as that of Sr I at 4607 Å) is (e.g., Trujillo Bueno & Manso Sainz 1999)

$$B_c = (1 + \delta)B_H, \quad (4.1)$$

where $\delta = D^{(2)}/A_{ul}$ is the collisional depolarizing rate (typically due to elastic collisions with neutral hydrogen atoms) in units of the Einstein A_{ul} coefficient for spontaneous emission, and

$$B_H = 1.137 \times 10^{-7} \frac{A_{ul}}{g_L} \quad (4.2)$$

is the magnetic strength for which the Zeeman splitting of the line's upper level is equal to its natural width (g_L being the level's Landé factor).

A first rough estimate of the Hanle-effect depolarization needed to explain some line scattering polarization observations of quiet regions of the solar atmosphere had suggested a tentative lower limit to the mean field strength $\langle B \rangle$ of 10 G (Stenflo 1982). In recent years the Hanle effect has changed from being considered an exotic theoretical (de)polarization mechanism to a powerful tool for the diagnostics of the solar magnetism. Recent advances in the Hanle-effect polarization diagnostics of the magnetism of the quiet solar photosphere are based on spectral lines like the molecular lines of C₂, MgH and CN (see Trujillo Bueno *et al.* 2004; Asensio Ramos & Trujillo Bueno 2005; Shapiro *et al.* 2011, and references therein), the lines of multiplet $a^5F - y^5F^o$ of Ti I (Manso Sainz *et al.* 2004; Shchukina & Trujillo Bueno 2009), and the Sr I 4607 Å line (Faurobert-Scholl *et al.* 1995; Faurobert *et al.* 2001; Shchukina & Trujillo Bueno 2003; Trujillo Bueno *et al.* 2004; Bommier *et al.* 2005; Trujillo Bueno & Shchukina 2007; Shchukina & Trujillo Bueno 2011). The Sr I line at 4607 Å is particularly convenient for the investigating the mean magnetization of the "quiet" solar photosphere thanks to its conspicuous scattering polarization signals (spatially and temporally averaged $\langle Q \rangle / \langle I \rangle \sim 1$ % near the solar limb) and its high sensitivity to the Hanle effect (between 10 and 250 G, approximately). In the next section we highlight some significant results obtained through the application of the Hanle effect in the Sr I 4607 Å line.

5. The Hanle Effect in the Sr I 4607 Å Line

Hanle-effect diagnostics using this line relies on a comparison between the observed scattering polarization Q/I signals and those corresponding to the zero-field reference case. The determination of the zero-field polarization amplitudes requires theoretical modeling. The quantum theory of spectral line polarization described in the monograph by Landi Degl'Innocenti & Landolfi (2004) is a very suitable theoretical framework for understanding the polarization produced in solar spectral lines for which correlations between the frequencies of the incoming and outgoing photons in the scattering events can be neglected, like that of Sr I at 4607 Å. In this theory, the excitation state of the atomic (or molecular) system is described by the *diagonal* and *non-diagonal* elements of the atomic density matrix corresponding to each atomic level of total angular momentum J , which quantify the level's overall population, the *population imbalances* between its sublevels, and the *quantum coherence* between each pair of them. Similarly, the symmetry properties of the radiation field are described by 9 tensors which quantify the mean

intensity, J_0^0 , the degree of anisotropy $\mathcal{A} = J_0^2/J_0^0$, and the breaking of the axial symmetry of the incident radiation field (e.g., due to horizontal atmospheric inhomogeneities).

A suitable model for estimating the Hanle depolarization in the Sr I 4607 Å line is that of a microturbulent field (i.e., that the “hidden” field has an isotropic distribution of orientations within a photospheric volume given by \mathcal{L}^3 , with \mathcal{L} the mean free path of the line-center photons). With this assumption for the topology of the “hidden” field and the two-level atom model (see Trujillo Bueno & Manso Sainz 1999) it is easy to obtain the following Eddington-Barbier approximation for estimating the line-center scattering polarization amplitude of the emergent radiation in the Sr I 4607 Å resonance line (see Shchukina & Trujillo Bueno 2003):

$$Q/I \approx \frac{3}{2\sqrt{2}} (1 - \mu^2) \frac{\mathcal{H}}{1 + \delta} \mathcal{A}. \quad (5.1)$$

In this approximate expression $\mu = \cos \theta$ (with the angle θ between the solar radius vector through the observed point and the line of sight), and \mathcal{H} represents the Hanle depolarization factor of the microturbulent field:

$$\mathcal{H} = 1/5 \times \{1 + 2/(1 + \Gamma^2) + 2/(1 + 4\Gamma^2)\}, \quad (5.2)$$

where

$$\Gamma \approx \gamma \times \frac{1}{1 + \delta} \quad (5.3)$$

and

$$\gamma = 8.79 \times 10^6 B g_L/A_{ul}. \quad (5.4)$$

The Hanle depolarization factor $\mathcal{H} = 1$ if the magnetic field strength $B = 0$ G, while $\mathcal{H} = 1/5$ for $B > 250$ G (i.e., $\mathcal{H} = 1/5$ for magnetic strengths larger than the Hanle saturation field of the Sr I 4607 Å line).

The approximate formula (5.1) shows clearly that a reliable estimation of the strength of the “hidden” photospheric field requires adopting realistic values for the collisional depolarizing rate δ , and determining the anisotropy \mathcal{A} of the spectral line radiation through radiative transfer calculations in realistic atmospheric models.

One-dimensional modeling. The first radiative transfer modeling of the scattering polarization observed in the Sr I 4607 Å line were one-dimensional, using a plane-parallel, static semi-empirical model of the quiet solar atmosphere and the above-mentioned microturbulent field model (Faurobert-Scholl *et al.* 1995; Faurobert *et al.* 2001). These authors concluded that the mean field strength around a height $h \approx 300$ km above the visible solar surface is between 10 and 25 gauss, assuming the single-valued microturbulent field model. Given that the atmospheric model used was one-dimensional and static, such modeling had to make use of the free parameters of stellar spectroscopy (that is, micro and macroturbulent velocities for the line broadening). As shown by Shchukina & Trujillo Bueno (2003) the choice made by Faurobert *et al.* for such free parameters yields artificially low values for the mean strength of the hidden field. This is because the scattering polarization amplitudes calculated by those authors for the zero-field reference case, $(Q/I)_{B=0}$, was seriously underestimated.

Three-dimensional modeling using a hydrodynamical (HD) model. The plasma of the solar atmosphere is inhomogeneous and dynamic, very different from a uniform static plane-parallel configuration. In order to improve the reliability of diagnostic tools based on the Hanle effect, Shchukina & Trujillo Bueno (2003), Trujillo Bueno *et al.* (2004) and Trujillo Bueno & Shchukina (2007) developed a new approach based on multilevel, non-LTE scattering polarization calculations in three-dimensional (3D) models of the solar

photosphere. In order to achieve a reliable calculation of the anisotropy of the spectral line radiation within the solar photosphere, it is very important to use realistic 3D models. They used a 3D photospheric model resulting from the hydrodynamical simulations of solar surface convection by Asplund *et al.* (2000). The detailed non-LTE studies of Fe I (Shchukina & Trujillo Bueno 2001), O I (Shchukina *et al.* 2005), Ti I (Shchukina & Trujillo Bueno 2009), Ba II (Shchukina *et al.* 2009), Si I (Shchukina *et al.* 2012), and of the intensity and polarization of the Sun's continuum spectrum (Trujillo Bueno & Shchukina 2009) show that this 3D HD model provides a suitable representation of the thermal and dynamical structure of the quietest regions of the Sun's photosphere.

The 3D radiative transfer approach allowed Trujillo Bueno *et al.* (2004) to achieve a reliable calculation of the linear polarization amplitudes that scattering processes in the solar photosphere would produce in the Sr I 4607 Å line if there were no magnetic field (see also Shchukina & Trujillo Bueno 2003). These authors confronted low resolution observations of the center-to-limb variation of the scattering polarization in the Sr I 4607 Å line with the Q/I signals that result from spatially averaging the emergent Q and I profiles calculated in the above-mentioned 3D HD model. The Stokes I , Q and Q/I profiles of the Sr I 4607 Å line that they used had been observed by several authors, both during a minimum and a maximum of the solar activity cycle (see references in Trujillo Bueno *et al.* 2004). The absence of any clear variation in the line-center amplitudes of the observed Q/I profiles suggested that they do not seem to be modulated by the solar cycle. Trujillo Bueno *et al.* (2004) found also that the synthetic intensity profiles of the Sr I 4607 Å line (which they obtained by taking fully into account the Doppler shifts of the convective flow velocities in the 3D model) are in good agreement with the Stokes- I observations when the meteoritic strontium abundance is chosen. However, the calculated Q/I line-center amplitudes turned out to be substantially larger than the observed ones. They used realistic values for the depolarizing rates due to elastic collisions with neutral hydrogen atoms (see equation 33 of Faurobert-Scholl *et al.* 1995) and concluded that such a significant discrepancy between the observed and calculated scattering polarization amplitudes indicated the presence of an unresolved, "hidden" magnetic field on sub-resolution scales.

In order to estimate the mean strength of such an unresolved magnetic field, Trujillo Bueno *et al.* (2004) used the microturbulent field model and two functional forms for the Probability Distribution Function, $PDF(B)$, describing the fraction of the 3D HD model occupied by magnetic fields of strength B . For the idealized case of a single-valued field ($PDF(B) = \delta(B - \langle B \rangle)$) they obtained $\langle B \rangle \approx 60$ at an atmospheric height of about 300 km, and a clear indication that $\langle B \rangle$ decreases with height in the quiet solar photosphere. † For the more realistic case of a $PDF(B) = (1/\langle B \rangle) \cdot \exp(-B/\langle B \rangle)$ the result was $\langle B \rangle \approx 130$ G at an atmospheric height of about 300 km, again with a clear indication that $\langle B \rangle$ is significantly larger in the low photosphere. This natural choice for the shape of the PDF (i.e., an exponential shape) was supported both by observations (e.g., Khomenko *et al.* 2003) and by numerical experiments of turbulent dynamos and magnetoconvection (e.g., Cattaneo 1999; Stein & Nordlund 2003). Trujillo Bueno *et al.* (2004) concluded that the magnetization of the quiet solar photosphere is very significant ($\langle B \rangle \approx 130$ G), substantially larger than the tentative lower limit to $\langle B \rangle$ of 10 G given by Stenflo (1982), or the 10–25 G given by Faurobert-Scholl *et al.* (1995) and Faurobert *et al.* (2001). With

† It is of interest to mention that this conclusion for the idealized case of a single-valued field was later confirmed by Bommier *et al.* (2005), who applied the 1D modeling approach with a more judicious choice than Faurobert-Scholl *et al.* (1995) and Faurobert *et al.* (2001) for the values of the micro and macroturbulent velocities.

$\langle B \rangle \approx 130$ G the magnetic energy density $E_m = \langle B \rangle^2 / 8\pi \approx 1300$ erg cm⁻³, which is a truly significant fraction ($\sim 10\%$) of the kinetic energy density produced by convective motions in the low photosphere of the HD model \ddagger . Trujillo Bueno *et al.* (2004) estimated the ensuing energy flux by using the typical value of 1 km s⁻¹ for the convective velocities (thinking in rising magnetic loops) or for the Alfvén speed (thinking in MHD waves), and concluded that in the upper solar photosphere it is about 10 times larger than that required to balance the chromospheric energy losses. Some recent investigations based on HINODE observations of the Zeeman effect in Fe I lines have supported this conclusion (e.g., Ishikawa & Tsuneta 2009; Martínez González *et al.* 2010).

The above-mentioned result (obtained from the Hanle effect in the Sr I 4607 Å line) may be summarized by saying that at a height of about 300 km above the visible solar surface $\langle B \rangle \approx 130$ G, when no distinction is made between the granular and intergranular regions. A second conclusion could be obtained through a joint analysis of the Hanle effect in C₂ lines and in the Sr I 4607 Å line. Trujillo Bueno *et al.* (2004) (see also Trujillo Bueno *et al.* 2006) found that while the plasma of the upflowing cell centers is weakly magnetized (with $\langle B \rangle \sim 10$ G), the downward-moving intergranular lane plasma is pervaded by relatively strong tangled magnetic fields at sub-resolution scales, with $\langle B \rangle$ larger than the Hanle saturation field of the Sr I 4607 Å line (i.e., with $\langle B \rangle > 250$ G).

Three-dimensional modeling using an MHD model with surface dynamo action.

Given that the 3D HD model is unmagnetized Trujillo Bueno *et al.* (2004) had to make the following two hypothesis on the unresolved magnetic field that produces Hanle depolarization: (1) the magnetic field is tangled at scales smaller than the mean free path of the line-center photons, with an isotropic distribution of directions and (2) the shape of the PDF is exponential. In order to determine the magnetization of the quiet Sun photosphere without using such two approximations, Shchukina & Trujillo Bueno (2011) have investigated the Hanle effect of the Sr I 4607 Å line in a 3D photospheric model resulting from the magneto-convection simulations with surface dynamo action of Vögler & Schüssler (2007) (hereafter, the MHD model), which show a complex small-scale magnetic field that results from dynamo amplification of a weak seed field.

The results of our investigation in the MHD model are summarized in Figs. 1 and 2. For the zero-field reference case, the scattering polarization Q/I amplitudes computed in the MHD model (after forcing the magnetic field strength to be zero at each spatial grid point) are similar to those obtained in the HD model (see Fig. 1, and compare the black open circles with the green filled circles). The small but noticeable differences between the two results are due to the fact that the thermodynamic structure of the MHD and HD models are not fully identical. The black dashed line of Fig. 1 shows that the Hanle depolarization in the Sr I 4607 Å line produced by the actual magnetic field of the MHD model (see dashed line of Fig. 2) is too small to explain the observed Stokes Q/I signals. This is because the average field strength at a height of about 300 km in the MHD model is only $\langle B \rangle \approx 15$ G (i.e., an order of magnitude smaller than the $\langle B \rangle$ value inferred by Trujillo Bueno *et al.* 2004). Clearly, the level of small-scale magnetic activity of the MHD surface dynamo model (whose magnetic Reynolds number is rather low, i.e. $R_m \approx 2600$) is significantly weaker than that of the real quiet Sun photosphere. The observed Q/I amplitudes can however be explained after multiplying each grid-point magnetic strength by a scaling factor $F = 12$ (see the dotted line in

\ddagger This result and the fact that the scattering polarization observed in the Sr I 4607 Å line does not seem to be modulated by the solar cycle, suggested that a small-scale dynamo associated with “turbulent” motions within a given convective domain of ionized gas plays a significant role for producing the “hidden” magnetic fields diagnosed through the Hanle effect.

Figs. 1 and 2), which implies that $\langle B \rangle \approx 130$ G in the upper photosphere of the model. As shown by the dotted line in Fig. 2, scaling the magnetic field strength of the MHD model with a constant factor $F = 12$ implies an unrealistic height-variation of the mean field strength $\langle B \rangle$. The resulting large magnetic field strength values in the region of formation of the Stokes V Zeeman signals of the FeI 6302.5 Å line (i.e., around 60 km in the MHD model) would produce synthetic Stokes profiles in contradiction with those observed. In fact, $F = 12$ is significantly larger than the tentative scaling factor $F = 3$ needed by Danilovic *et al.* (2010) for explaining the histograms of the polarization signals produced by the Zeeman effect in the FeI lines at 6301.5 Å and 6302.5 Å. On the other hand, $F = 3$ is too low a value for explaining the Q/I observations of Fig. 1.

Therefore, in order to explain both the Hanle depolarization of the SrI 4607 Å line and the Zeeman signals in the FeI lines, Shchukina & Trujillo Bueno (2011) scaled the magnetic strength of the MHD model by a height-dependent factor, $F(h)$, varying between $F \approx 3$ at $h \approx 0$ km and $F \approx 12$ at $h \approx 300$ km (see the black solid curves in Figs. 1 and 2). With this height-dependent scaling factor, which implies $\langle B \rangle \approx 160$ G in the low photosphere and $\langle B \rangle \approx 130$ G in the upper photosphere, it is possible to explain

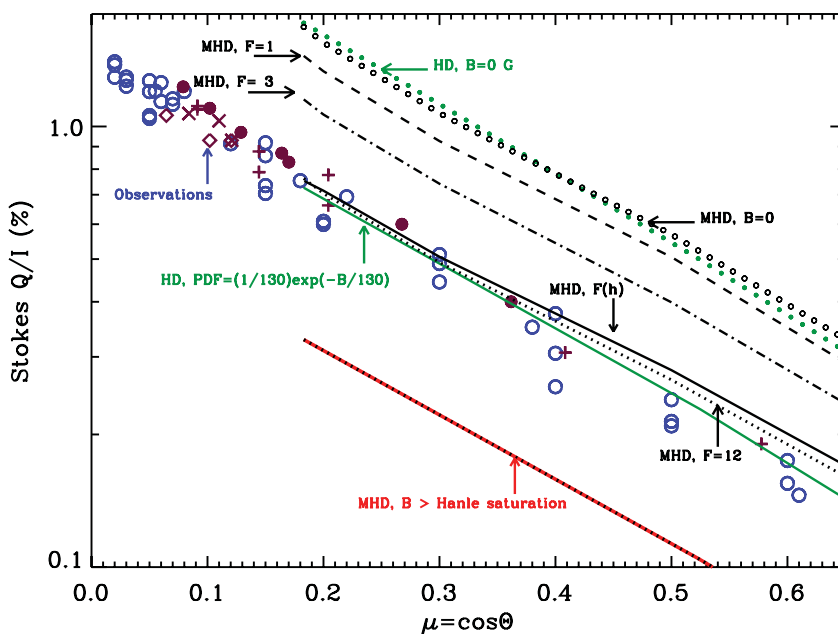


Figure 1. Center-to-limb variation of the spatially averaged Q/I scattering amplitudes of the SrI 4607 Å line. The different symbols correspond to various observations taken by several authors during a minimum and a maximum of the solar activity cycle (see references in Trujillo Bueno *et al.* 2004). The two green lines show scattering polarization amplitudes calculated in the HD model, without including any magnetic field (green filled circles) and including the Hanle depolarization of a microturbulent field with an exponential PDF characterized by a mean field strength $\langle B \rangle = 130$ G (green dashed-tree-dotted line). The black lines show Q/I amplitudes calculated in the MHD model, neglecting its magnetic field (black open circles) and taking into account the Hanle depolarization of the model's magnetic field (black dashed line, $F = 1$). As shown by the black solid line, the observations can be approximately fitted by multiplying each grid-point magnetic strength by a height-dependent factor $F(h)$ (which implies the height variation of $\langle B \rangle$ given by the solid line of Fig. 2). Practically the same result is obtained with a constant scaling factor $F = 12$ (which implies the unrealistic height variation of $\langle B \rangle$ given by the dotted line of Fig. 2). The red solid line shows the calculated scattering polarization amplitudes when imposing $B > B_{\text{sat}} = 250$ G at each grid point in the MHD model.

both the scattering polarization observed in the Sr I 4607 Å line and the Zeeman signals observed with HINODE in the Fe I lines. Note that with the assumed height-dependent scaling factor the scattering polarization amplitudes of the Sr I 4607 Å line computed in the MHD model are close to the values calculated in the HD model assuming a microturbulent field with an exponential PDF characterized by $\langle B \rangle = 130$ G (dashed-three-dotted line in Fig. 1). It is also noteworthy that in the MHD model whose magnetic strength has been scaled with $F(h)$, a significant fraction of the model's granular plasma that contributes to the scattering polarization of the C₂ lines is magnetized with $\langle B \rangle \sim 10$ G. We can thus conclude that the investigation by Shchukina & Trujillo Bueno (2011) reinforces the conclusions of Trujillo Bueno *et al.* (2004).

6. Concluding comments

Information on our investigations of the Hanle effect in 3D models of the quiet solar photosphere can be found in Shchukina & Trujillo Bueno (2003), Trujillo Bueno *et al.* (2004), Asensio Ramos & Trujillo Bueno (2005), Trujillo Bueno *et al.* (2006), Trujillo Bueno & Shchukina (2007) and Shchukina & Trujillo Bueno (2011). Here we summarize the main results:

- The quiet solar photosphere is permeated by a small-scale magnetic field, whose average strength varies approximately between $\langle B \rangle \approx 160$ G in the low photosphere

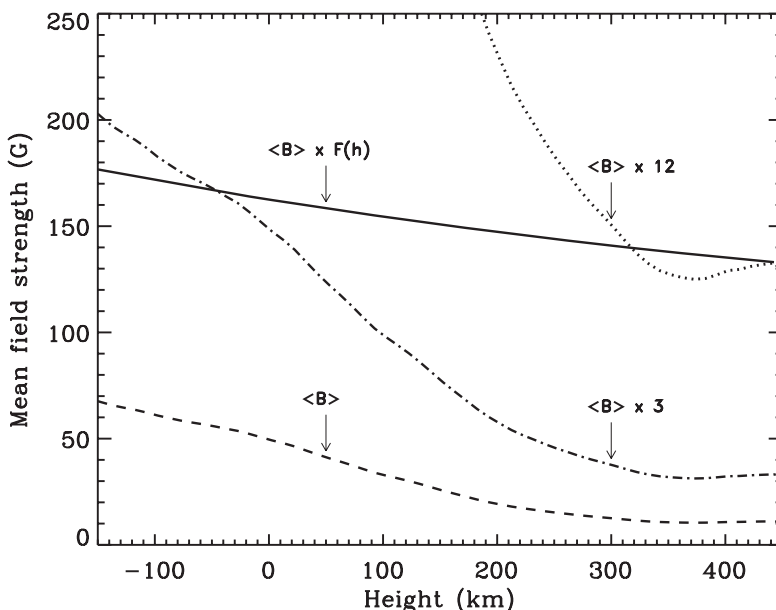


Figure 2. Height-variation of the mean field strength corresponding to four scaling factors F of the magnetic strength of the MHD model. Dashed-line: $F = 1$ (i.e., as in the original MHD model). Dashed-dotted line: $F = 3$ (i.e., as suggested by the Zeeman polarization investigation of Danilovic *et al.* 2010). Dotted line: $F = 12$. Solid line: a height-dependent scaling factor that explains simultaneously the center-to-limb variation of the observed scattering polarization Q/I in the Sr I 4607 Å line and the Zeeman effect polarization in the Fe I 6302.5 Å line observed with the spectropolarimeter of the Solar Optical telescope onboard of the Hinode satellite (Tsuneta *et al.* 2008). The arrows at $h \approx 60$ km and $h \approx 300$ km indicate the approximate atmospheric heights around which the observed Zeeman and Hanle signals are produced, respectively.

($h \approx 60$ km) and $\langle B \rangle \approx 130$ G in the upper photosphere ($h \approx 300$ km), when no distinction is made between granular and intergranular regions.

- Such a magnetic field is organized at the spatial scales of the solar granulation pattern, with relatively weak fields above the granule cell centers and with much stronger fields above the intergranular lanes.

- In the upper photosphere, the energy flux estimated using the typical value of 1 km s^{-1} for the convective velocity (thinking in rising magnetic loops) or the Alfvén speed (thinking in MHD waves) turns out to be an order of magnitude larger than that required to balance the radiative energy losses from the solar chromosphere.

- The downward-moving intergranular lane plasma is pervaded by relatively strong tangled magnetic fields at sub-resolution scales, with $\langle B \rangle > 250$ G. This conclusion implies that most of the flux and magnetic energy reside on still unresolved scales in the intergranular plasma. This leads us to speculate that it is here in the turbulent downdrafts where significant “local” dynamo action is taking place.

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