The quiet solar photosphere is permeated by a small-scale tangled magnetic field, whose average strength at heights \( h \approx 300 \text{ km} \) above the visible solar surface is \( \langle B \rangle \approx 130 \text{ G} \) when no distinction is made between granular and intergranular regions.

2. The downward-moving intergranular lane plasma is pervaded by relatively strong tangled magnetic fields at subresolution scales, with \( \langle B \rangle > 200 \text{ G} \). This conclusion suggests that most of the flux and magnetic energy reside on still unresolved scales.

3. In the upper photosphere, the ensuing energy flux estimated using the typical value of \( 1 \text{ km s}^{-1} \) 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 radiative energy losses from the quiet chromosphere.

The first conclusion was obtained by contrasting low resolution observations of the scattering polarization signals of the Sr I 4607 Å line with three-dimensional (3D) radiative transfer calculations in a realistic 3D model of the quiet solar photosphere obtained from the hydrodynamical (HD) simulations of Asplund et al. (2000, hereafter the HD model). The second conclusion resulted from combining the information provided by the strontium line with that which we obtained through the application of the Hanle effect line ratio technique for C II lines explained carefully in Trujillo Bueno et al. (2006). It is, however, important to note that the above-mentioned HD model is unmagnetized and that, therefore, such conclusions are based on the following hypotheses for the quiet Sun 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 probability density function (PDF), describing the fraction of the quiet Sun photosphere occupied by magnetic fields of strength \( B \), is exponential (PDF\( (B) = \frac{1}{\sqrt{2\pi}}e^{-B/\langle B \rangle} \)).

The main aim of this Letter is to determine the strength of the magnetization of the quiet solar photosphere without making use of such two approximations. To this end, we investigate the Hanle effect of the Sr I 4607 Å line in a 3D photospheric model resulting from the magnetohydrodynamic (MHD) simulations of Vögler & Schüssler (2007), which show a complex small-scale magnetic field that results from dynamo amplification of a weak seed field. These authors went a step further than Cattaneo (1999) by demonstrating that a realistic flow topology of stratified, compressible, surface convection without enforced recirculation is capable of local dynamo action near the solar surface. It is interesting to note that the small-scale “hidden magnetic field” inferred via the Hanle effect lends support to the notion of a turbulent solar surface dynamo playing a significant role in the magnetism of the quiet Sun (e.g., Pietarila Graham et al. 2009; see also the reviews by Lites 2009, and by Sánchez Almeida & Martínez González 2011).

2. FORMULATION OF THE HANLE-EFFECT PROBLEM IN 3D MAGNETO-CONVECTION MODELS

We calculated the number density of Sr I atoms at each grid point of a 3D MHD model resulting from a non-gray radiative transfer version of the Run-C simulation of Vögler & Schüssler (2007, hereafter, the MHD model). To this end, we solved the
standard 3D non-LTE problem without polarization including all the allowed radiative and collisional transitions between the 15 bound levels of a realistic model of Sr\textsc{i} and the ensuing ionizing transitions to the ground level of Sr\textsc{ii}. With the resulting number density of Sr\textsc{i} atoms fixed, we solved the full 3D radiative transfer problem of the scattering polarization in the Sr\textsc{i} 4607 Å line by applying the complete frequency redistribution theory of resonance-line polarization (e.g., Landi Degl’Innocenti & Landolfi 2004), which is suitable for modeling the fractional linear polarization observed in weak resonance lines like that of Sr\textsc{i} at 4607 Å (see Sampoorna et al. 2010; and references therein).

The Sr\textsc{i} line at 4607 Å results from a single ^1S\textsc{iii} − ^1P\textsc{i} resonance-line transition with \( J_f = 0 \) and \( J_i = 1 \) (the total angular momentum of its lower and upper levels, respectively). Although the ensuing Einstein coefficient for spontaneous emission is very large (i.e., \( A_{\text{ul}} \approx 2 \times 10^5 \text{s}^{-1} \)), the line originates in the solar photosphere because the abundance of strontium is relatively low (see Figure 1). Scattering polarization in the Sr\textsc{i} 4607 Å line is caused only by the atomic polarization (population imbalances and quantum coherences) of its upper level, which results from anisotropic radiation pumping in the solar photosphere. The lower level cannot be polarized and the relevant transfer equations for modeling the available low-resolution observations of the fractional linear polarization signals are \( \frac{d\tau}{dr} X = X - S_X \), with \( X \) being the Stokes parameter \( I, Q, O \) or \( U \) at the frequency and direction of propagation under consideration (\( d\tau = -\eta I ds \) defines the monochromatic optical path along the ray, \( \eta \) being the absorption coefficient and \( s \) the geometrical distance).

The source function components are \( S_I = r S_{\text{line}}^I + (1 - r) B \), \( S_O = r S_{\text{line}}^O \), and \( S_U = r S_{\text{line}}^U \), where \( B \) is the Planck function and \( r = \kappa_{\text{ul}}/\kappa_{\text{ul}} + \kappa_{\text{c}} \) (with \( \kappa_{\text{c}} \) being the line-integrated opacity, \( \kappa_{\text{c}} \) the continuum opacity, and \( \kappa_{\text{ul}} \) the normalized absorption profile). The expressions of the line source function components are identical to those used by Trujillo Bueno & Shchukina (2007), which are functions of the inclination and azimuth of the ray under consideration and of the following position-dependent quantities (with \( Q = 0 \) for \( K = 0 \), and \( Q = 0, 1, 2 \) for \( K = 2 \)): \( \rho^K_S = \frac{\Delta \omega^K J^K}{\sqrt{\Delta \omega^K}} \rho^K_{B} \) (with \( \rho^K_{B} \) the multipolar components of the upper-level density matrix normalized to the overall population of the ground level). Note that \( \rho^K_S \) (with \( Q = 1, 2 \)) are complex quantities; thus, we will use \( \rho^K_{S_0} \) and \( \rho^K_{S_1} \) to denote, respectively, the real and imaginary parts of \( \rho^K_S \). The values of such quantities at each spatial grid point have to be found by solving the following coupled set of equations (Manso Sainz & Trujillo Bueno 1999):

\[
S_0^0 = (1 - \epsilon) J_0^0 + \epsilon B_v, \tag{1}
\]

\[
\begin{pmatrix}
S_0^0 \\
S_0^1 \\
S_0^2
\end{pmatrix} = \frac{1 - \epsilon}{1 + \delta^{(2)}(1 - \epsilon)}
\begin{pmatrix}
J_0^0 \\
J_1^0 \\
J_2^0
\end{pmatrix} - \frac{1 - \epsilon}{1 + \delta^{(2)}(1 - \epsilon)} \Gamma_u
\begin{pmatrix}
\rho^K_{S_0} \\
\rho^K_{S_1} \\
\rho^K_{S_2}
\end{pmatrix}, \tag{2}
\]

where \( \epsilon = C_0/(A_0 + C_0) \) (with \( C_0 \) the rate of inelastic collisions with electrons, in \( \text{s}^{-1} \)), \( \Gamma_u = 8.79 \times 10^6 \gamma_B A_{\text{ul}} / g_u \) (with \( g_u \) the Landé factor of the upper level and \( B \) the magnetic strength in gauss), \( \delta^{(2)} = D^{(2)} / A_{\text{ul}} \) (with \( D^{(2)} \) the upper-level depolarizing rate due to elastic collisions with neutral hydrogen atoms), and \( w_{10}^{(2)} = 1 \). In these expressions, \( J^K_0 \) (with \( Q = 0 \) for \( K = 0 \) and \( Q = 0, 1, 2 \) for \( K = 2 \)) are the spherical components of the radiation field tensor (Landi Degl’Innocenti & Landolfi 2004), which are integrals over the frequency and direction of the Stokes parameters weighted by the normalized absorption profile. Thus, \( J^K_0 \) quantifies the familiar mean intensity of the incident radiation, \( J^K_1 \) its anisotropy, while \( J^K_2 \) and \( J^K_2 \) (with \( Q = 1, 2 \) denote, respectively, the real and imaginary parts of \( J^K_0 \) which measure the breaking of the axial symmetry of
the depolarizing rate, $\delta^{(2)} = D^{(2)}/A_{\text{ul}}$, is proportional to the neutral hydrogen number density (see Equation (33) in Faurobert-Scholl et al. 1995). Such a formula for calculating $\delta^{(2)}$ results from an accurate quantum mechanical derivation, and we point out that it leads to values similar to those we have obtained through the semi-classical theory of Anstee & O’Mara (1995).

The excellent agreement between the $\delta^{(2)}$ values of our modeling, because the SrI 4607 Å line is a triplet type transition with spin $S = 0$ (i.e., it is a spectral line for which the classical description holds).

Of particular interest is the fact that the magnetic strength needed to reach any given depolarization is the larger the greater $\delta^{(2)}$. This can be seen in the expression of the critical magnetic field strength for the onset of the Hanle effect, which can be inferred through the semi-classical theory of Anstee & O'Mara (1995). Equation (A16) of Trujillo Bueno & Manso Sainz (1999) implies that

$$B_c \approx (1 + \delta^{(2)}) B_H,$$

where $B_H = 1.137 \times 10^{-7} A_{\text{ul}}/g_{\text{D}}$ is the critical Hanle field in the collisionless regime (i.e., $B_H \approx 23$ G for the SrI 4607 Å line). We point out that in the atmospheric region of formation of the SrI 4607 Å line (i.e., approximately between 250 km and 350 km for lines of sight with $0.6 \mu \geq 0.1$ in the MHD model) the horizontally averaged $B_i$ value varies between 60 G and 40 G, approximately, with $B_i$ decreasing with height because $\langle \delta^{(2)} \rangle$ decreases with height in the solar atmosphere (following the density decrease). More or less similar $B_i$ values are found in one-dimensional semi-empirical models. It is also important to note that a lower limit for the Hanle saturation field of the SrI 4607 Å line is $B_{\text{satur}} = 200$ G $\approx 10$ $B_H$, since full saturation is reached only for $B \geq 300$ G.

3. RESULTS

The results reported here were obtained through the self-consistent numerical solution of the equations, applying the methods mentioned in Trujillo Bueno & Shchukina (2007). In a first step we solved the scattering line polarization problem of the SrI 4607 Å line in the MHD surface dynamo model, but imposing $B = 0$ G at each spatial grid point. The resulting $Q/I$ and $U/I$ line-center signals are similar to those shown for three lines of sight in Figure 1 of Trujillo Bueno & Shchukina (2007), which were obtained by solving the same 3D radiative transfer problem in the above-mentioned HD model. For the moment, the scattering polarization observations of the SrI 4607 Å line that have been published lack spatial resolution (see Figure 2). We point out that when the $I$, $Q$, and $U$ profiles we have calculated in the MHD model are spatially averaged over scales significantly larger than that of the solar granulation pattern, we obtain $U/I \approx 0$ and the $Q/I$ line-center amplitudes given by the black open circles of Figure 2. Remarkably, these reference scattering polarization amplitudes are similar to those computed by Trujillo Bueno et al. (2004) in the HD model (see the green open circles). The small but noticeable differences between the two curves are due to the fact that the thermodynamic structure of the MHD model is not as accurate as in the HD model, including the Hanle depolarization of a microturbulent field with an exponential PDF characterized by a mean field strength $B = 130$ G (green dashed line). The black lines show scattering polarization 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 with scaling factors $F = 1$ (black dashed line) and $F = 3$ (black dash-dotted line). 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 $B$ given by the solid line of Figure 3). Practically the same black solid line is obtained with a constant scaling factor $F = 12$ (which implies the unrealistic height variation of $B$ given by the dotted line of Figure 3). The red solid line shows the calculated scattering polarization amplitudes when imposing $B > B_{\text{sat}} = 300$ G at each grid point in the MHD model. The fact that this red line coincides with 1/5 of the zero-field $Q/I$ amplitudes indicates that the microturbulent field approximation is indeed a suitable one.

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5 For this reason, we find again $\langle B \rangle \approx 130$ G when the same hypotheses mention in Section 1 are used to infer $\langle B \rangle$ from calculations in the $B = 0$ G version of the MHD model.
solid and dashed lines that observed Zeeman and Hanle signals are produced, respectively. Note from the \( \approx \) 60 km induced by the Zeeman effect in the Fe\textsubscript{i} without destroying the possibility of explaining simultaneously the polarization that explains the scattering polarization observations of the Sr\textsubscript{i}.

It is also important to mention that a significant fraction of the model’s granular plasma that contributes to the scattering polarization of the C\textsubscript{2} lines mentioned in Section 1 is magnetized with \( \langle B \rangle \approx 10\) G.

4. CONCLUSIONS

We have solved the radiative transfer problem of resonance polarization and the Hanle effect of the Sr\textsubscript{i} 4607 Å line in a 3D model of the quiet solar photosphere resulting from the magneto-convection simulations with surface dynamo action of Vogler & Schüssler (2007). We find that the level of magnetic activity in their surface dynamo model is too low for explaining the scattering polarization observations of the Sr\textsubscript{i} 4607 Å line. The observed linear polarization amplitudes can however be explained after multiplying each grid-point magnetic strength by a scaling factor \( F \approx 12 \).

A scaling factor \( F \approx 12 \) is about three or four times larger than that required to explain the polarization induced by the Zeeman effect in the Fe\textsubscript{i} lines around 6302 Å. This discrepancy between the scaling factors needed to explain the Hanle signals of the Sr\textsubscript{i} 4607 Å line and the Zeeman signals of the Fe\textsubscript{i} lines disappears if we take into account that the Zeeman signals originate a few hundred kilometers deeper than the Hanle signals (see Figure 1). In other words, with a height-dependent scaling factor that 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 approximately both types of observations.

Our investigation of the Hanle effect in the above-mentioned surface dynamo model reinforces the conclusions of Trujillo Bueno et al. (2004) summarized in Section 1. In particular, the horizontal variation of the scaled magnetic field needed to fit the observations indicates that most of the flux and magnetic energy reside on still unresolved scales in the intergranular plasma. Moreover, the fact that the magnetic energy density carried by this “hidden” magnetic field is a significant fraction of the local kinetic energy density and that the scattering polarization amplitudes of the Sr\textsubscript{i} line and of the C\textsubscript{2} lines do not seem to be clearly modulated by the solar cycle (Trujillo Bueno et al. 2004; Kleint et al. 2010) support the suggestion that a small-scale turbulent surface dynamo plays a significant role in the magnetism of the “quiet” Sun.

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\textsuperscript{6} The small discrepancy between the black solid line and the data points of Figure 2 can be explained by the fact that the thermal and density structure of the MHD model is not as accurate as that of the HD model.
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