THE SCATTERING POLARIZATION OF THE Sr i 4607 LINE AT THE DIFFRACTION LIMIT RESOLUTION OF A 1 m TELESCOPE

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Received 2007 May 16; accepted 2007 June 13; published 2007 July 23

ABSTRACT

One of the greatest challenges in solar and stellar physics in the coming years will be to observe the second solar spectrum with a spatial resolution significantly better than 1". This type of scattering polarization observation would probably allow us to discover hitherto unknown aspects of the Sun’s hidden magnetism. Here we report on some theoretical predictions for the photospheric line of Sr i at 4607 Å, which we have obtained by solving the three-dimensional (3D) radiative transfer problem of scattering line polarization in a realistic hydrodynamical model of the solar photosphere. We have taken into account not only the anisotropy of the radiation field in the 3D medium and the Hanle effect of a tangled magnetic field, but also the symmetry-breaking effects caused by the horizontal atmospheric inhomogeneities produced by the solar surface convection. Interestingly, the Q/I and U/I linear polarization signals of the emergent spectral line radiation have sizable values and fluctuations, even at the very center of the solar disk where we observe the forward-scattering case. The ensuing small-scale patterns in Q/I and U/I turn out to be sensitive to the assumed magnetic field model and are of great diagnostic value. We argue that it should be possible to observe them with the help of a 1 m telescope equipped with adaptive optics and a suitable polarimeter.

Subject headings: polarization — radiative transfer — scattering — stars: magnetic fields — Sun: magnetic fields — Sun: photosphere

1. INTRODUCTION

The observation and modeling of the spectral line polarization produced by radiatively induced quantum coherences in atomic systems provide us with a novel diagnostic window to explore the magnetism of the Sun and of other stars via the Hanle effect (see, e.g., the recent monograph by Landi Degl’Innocenti & Landolfi 2004). For the moment, such scattering polarization signals have been observed without or with poor spatial and/or temporal resolution (e.g., Stenflo & Keller 1997; Trujillo Bueno et al. 2001; Malherbe et al. 2007). However, as shown in this work, there are important scientific reasons to try to observe them with a spatial resolution significantly better than 1", so as to be able to see clearly the details of the solar granulation pattern.

In the apparently quiet regions of the solar atmosphere, there are three main reasons for expecting spatial variability in the linear polarization signals produced by scattering processes. First, the atmospheric inhomogeneities produced by the solar surface convection lead to horizontal fluctuations in the anisotropy of the radiation field, which must have their impact on the polarization of the emergent radiation (Trujillo Bueno 2003; Trujillo Bueno et al. 2004). Second, the same atmospheric inhomogeneities should lead to local symmetry-breaking effects, so that the radiation field loses the axial symmetry that is characteristic of a plane-parallel or spherically symmetric stellar atmosphere model. As a result, as pointed out by Manso Sainz & Trujillo Bueno (1999) through two-dimensional radiative transfer calculations in simplified solar model atmospheres, one can have scattering line polarization even at the center of the solar disk, without the need of an inclined magnetic field. Third, the scattering polarization signals are sensitive to magnetic fields via the Hanle effect and could therefore show fluctuations across the observed field of view if the statistical properties of the hidden field are not homogeneous, as is indeed indicated by a joint analysis of the Hanle effect in atomic and molecular lines (Trujillo Bueno et al. 2004, 2006).

In this Letter we present simulated polarimetric observations for the well-known case of the Sr i 4607 line, which we have obtained by solving the radiative transfer problem of scattering line polarization in a realistic three-dimensional (3D) hydrodynamical model of solar surface convection. Observations of the spatial variations of the scattering polarization in the Sr i 4607 line have shown that these variations are very small and next to invisible with the resolution used (e.g., Stenflo et al. 1997; Trujillo Bueno et al. 2001; Malherbe et al. 2007), in contrast to the large spatial variations in Q/I and U/I seen in much stronger lines like Ca i 4227 (e.g., Fig. 5 in Stenflo 2004) and Ca ii K (e.g., Fig. 4 in Stenflo 2006), which have been tentatively interpreted in terms of largely resolved magnetic fields in the solar chromosphere. While the chromosphere has prominent inhomogeneities on supergranular scales, which are well resolved in the observations mentioned, the quiet photosphere varies on the scale of the solar granulation, which has so far been below the resolution that has been achieved in combination with high-precision spectropolarimetry.

In our previous 3D radiative transfer investigations (Shchukina & Trujillo Bueno 2003; Trujillo Bueno et al. 2004), only the influence of the mean intensity and anisotropy of the Sr i 4607 line radiation was accounted for. Here we consider the full 3D scattering line polarization problem in the same realistic hydrodynamical model of the solar photosphere, including the Hanle effect of a microturbulent magnetic field but taking into account the above-mentioned symmetry-breaking effects that we had previously neglected. As we shall see, we confirm our conclusions concerning the presence of a substantial amount of hidden magnetic energy in the quiet regions of the solar photosphere. In addition, we report on the new interesting results summarized in the abstract.
2. FORMULATION OF THE PROBLEM

We have solved the 3D scattering polarization problem for the Sr I λ4607 line in a realistic model of the solar photosphere resulting from the hydrodynamical simulations of solar surface convection by Asplund et al. (2000).

First, we calculated the number density of Sr I atoms at each grid point of the 3D photospheric model and the overall population of the lower and upper levels of the λ4607 line transition, whose total angular momentum values are J_l = 0 and J_u = 1, respectively. To this end, we solved the standard non-LTE radiative transfer problem, including all the allowed radiative and collisional transitions between the 15 bound levels of a realistic model of Sr I and the ensuing ionizing transitions to the ground level of Sr II. It is important to calculate the ionization balance of strontium without assuming LTE and by using a realistic atomic model in order to account properly for the UV overionization mechanism by means of which all the Sr I levels become significantly underpopulated with respect to the LTE case (Shchukina & Trujillo Bueno 2003). We point out that with the resulting self-consistently calculated populations, the computed spatially averaged emergent intensity profiles (which take into account the Doppler shifts of the convective flow velocities in the 3D model) turn out to be in excellent agreement with the observations.

Our second step consisted in calculating, at each grid point of the 3D model, the self-consistent values of the six multipolar components of the atomic density matrix that characterize the excitation state of the upper level of Sr I λ4607 line transition, using the previously calculated lower level population values. Such density-matrix elements quantify the overall population of the upper level (via the ρ_u(l) component), the level’s population imbalances (via the ρ_u(0) component), and the quantum coherences between each pair of magnetic sublevels pertaining to the upper level (via the real and imaginary parts of the ρ_u(1) and ρ_u(2) components). To this end, we solved iteratively the set of equations that results from combining the radiative transfer equations for the Stokes parameters I, Q, and U and the following statistical equilibrium equations, whose derivation can be found in Appendix A of Trujillo Bueno & Manso Sainz (1999):

\[ S_0^l = (1 - ϵ)J_0^l + ϵB_u, \]  
\[ \left[ 1 + δ^{(2)}(1 - ϵ) \right] \begin{pmatrix} S_0^l \\ S_1^l \\ S_2^l \end{pmatrix} = (1 - ϵ)w_{J,J_0}^{(2)}H^{(2)} \begin{pmatrix} J_0^l \\ J_1^l \\ J_2^l \end{pmatrix}. \]  

In these expressions, which are valid for the case of a resonance line without lower level polarization, B_u is the Planck function, \( S_0^l = (2\pi\hbar)c^3/(2J_u + 1)(2J_l + 1)\epsilon_J^l \) (with \( ρ_J^l \) the density-matrix elements of the upper level normalized to the overall population of the ground level), and \( J_0^l \) are the spherical components of the radiation field tensor (see, e.g., § 5.11 in Landi Degl’Innocenti & Landi 2004). We point out that \( S_0^l \) and \( J_0^l \) (with \( Q = 1, 2 \)) are complex quantities and that in equation (2), \( S_0^l \) and \( J_0^l \) indicate the real parts, while \( S_1^l \) and \( J_1^l \) indicate the imaginary parts. The expressions that we have used for \( J_0^l, J_1^l, \) and \( J_2^l \) (with \( Q = 1, 2 \)) are those given by equations (4)–(7) in Trujillo Bueno (2001), taking into account the Doppler shifts caused by the convective velocities. Note also that \( H^{(2)} \) is the Hanle depolarization factor of a microturbulent magnetic field (see eq. [A.16] in Trujillo Bueno & Manso Sainz 1999), \( ϵ \) is the collisional destruction probability due to inelastic collisions with electrons, \( δ^{(2)} = D^{(2)}/A_w \) is the collisional depolarizing rate due to elastic collisions with neutral hydrogen atoms measured in units of the Einstein \( A_w \) coefficient, and \( w_{J,J_0}^{(2)} \) is a coefficient whose value is unity for the Sr I λ4607 line under consideration.

The spherical components of the radiation field tensor are given by angular- and frequency-weighted averages of the Stokes parameters. Thus, \( J_0^l \) quantifies the mean intensity of the spectral line radiation, \( J_1^l \) the anisotropy factor, and \( J_2^l \) (with \( Q = 1, 2 \)) the breaking of the axial symmetry of the radiation field through the complex azimuthal exponentials that appear inside the angular integrals (i.e., \( e^{i\chi} \) for \( J_1^l \) and \( e^{i\chi} \) for \( J_2^l \), where \( \chi \) is the azimuth of the ray). We point out that while \( J_1^l \) and \( J_2^l \) are zero in a plane-parallel or spherically symmetric model atmosphere in the absence or in the presence of a microturbulent magnetic field, they turn out to fluctuate horizontally at each height in the above-mentioned 3D hydrodynamical model of the solar photosphere, with sizable positive and negative values mainly around the boundaries between the granular and intergranular regions.

The statistical equilibrium equations have a clear physical meaning. In particular, equation (2) describes the transfer of the symmetry properties of the radiation field directly to the atomic system. Therefore, without the need of a magnetic field (i.e., for \( H^{(2)} = 1 \)), optical pumping processes can generate both population imbalances (if \( J_0^l \neq 0 \)) and coherences (if \( J_0^l \neq 0 \)).

In the presence of a microturbulent magnetic field, the population imbalances (\( S_0^l \)) and the quantum coherences (\( S_1^l \) and \( S_2^l \)) are reduced because \( H^{(2)} \) varies between 1 (for \( B = 0 \) G) and 0.2 (for \( B > 10 \) B, where \( B \approx (1 + δ^{(2)}) \times 10^{-7}A_w/g_a \) with \( g_a \) the Landé factor of the upper level).

Our numerical solution for this physical problem is based on the iterative methods developed by Trujillo Bueno & Manso Sainz (1999), which require calculating the radiation field tensors \( J_0^l \) at each iterative step. Since the lower level of the Sr I λ4607 line has \( J_l = 0 \), it cannot be polarized. Therefore, the transfer equation for Stokes X (with \( X = I, Q, U \)) is simply given by

\[ dX/dτ = X − S_X, \]

which we have solved by applying the 3D formal solver of Fabiani Bendicho & Trujillo Bueno (1999). The line contributions to \( S_q \) and \( S_u \) are the following (e.g., Manso Sainz & Trujillo Bueno 1999):

\[ S_q^{\text{line}} = w_{J,J_0}^{(2)} [ \frac{3}{2\sqrt{2}} (\mu^2 − 1)S_0^l ] \]
\[ \quad \frac{3}{2} \mu \sin(\chi)S_1^l + \cos(\chi)S_2^l \]
\[ S_u^{\text{line}} = w_{J,J_0}^{(2)} [ \frac{3}{2\sqrt{2}} (\mu^2 − 1)S_0^l ] \]
\[ \quad \frac{3}{2} \mu \sin(\chi)S_1^l + \cos(\chi)S_2^l \]

where the orientation of the ray is specified by \( \mu = \cos \theta \) (with \( \theta \) being the polar angle) and by the azimuthal angle \( \chi \). The exact expression for \( S_1^{\text{line}} \) that we have used in our calculations is as
FIG. 1.—Emergent $Q/I$ (top panels) and $U/I$ (bottom panels) at the line center of the Sr I λ4607 line calculated for three lines of sight in a 3D snapshot of a realistic hydrodynamical simulation of solar surface convection and accounting for the diffraction limit effect of a 1 m telescope. The positive reference direction for Stokes $Q$ lies along the vertical direction of the corresponding panel, which for the $\mu = 0.1$ and $\mu = 0.5$ cases coincides with the parallel to the limb of the solar model. Note that we have taken into account the projection effects by means of which the off-disk-center images appear contracted by a factor $\mu$ along the horizontal direction of the figure panels. Note also that the “surface distances” given in the plots measure the true separation between the points on the actual surface of the solar model. The solid-line contours in the $\mu = 1$ panels delineate the (visible) upflowing granular regions.

complicated as the two previous ones (see eq. [14] in Manso Sainz & Trujillo Bueno 1999), but in a weakly anisotropic medium like the solar photosphere, $S_0^{\text{line}} \approx S_0^J$. Note also that at the line center of a significantly strong spectral line, an approximate expression for estimating the emergent fractional linear polarization is $X/I \approx S_0^{\text{line}}/I^\text{line}$ (for $X = Q, U$), with the corresponding source-function values calculated at the atmospheric height where the line-center optical depth is unity along the line of sight.

It is important to point out that the above-mentioned asymmetry-breaking effects imply nonzero values for $J_2^J$ and $J_2^Q$, which in turn imply nonzero values for $S_2^J$ and $S_2^Q$ (see eq. [2]). Note also from equations (3) and (4) that their main observable effects would be nonzero Stokes $Q/I$ and $U/I$ signals at the solar disk center ($\mu = 1$) and nonzero Stokes $U/I$ signals at any off-disk-center position. Let us now show how large such fractional polarization signals are expected to be at three on-disk positions ($\mu = 0.1$, $\mu = 0.5$, and $\mu = 1$), taking into account the diffraction limit effect of a 1 m telescope (which we have accounted for through convolution with the Airy function).

3. THE EFFECTS OF SYMMETRY BREAKING ON THE SCATTERING LINE POLARIZATION

Figure 1 shows the center-to-limb variation of the $Q/I$ and $U/I$ line-center signals of the Sr I λ4607 line, which we have obtained by solving the scattering line polarization problem in the above-mentioned 3D hydrodynamical model without magnetic fields. We point out that in each panel of Figure 1, there are some points of the field of view with signals outside the minimum and maximum values that we have chosen to optimize the visualization.

As expected, at $\mu = 0.1$ and $\mu = 0.5$ (see the left and middle top panels of Fig. 1), the $Q/I$ signals are almost everywhere positive, because far away from the solar disk center the term of equation (3) proportional to $S_0^J$ makes the dominant contri-

4. In the absence of magnetic fields, $Q/I$ at $\mu = 0.1$ varies between about 1% and 4%, while the range of variation at $\mu = 0.5$ lies between −0.14% and 1.55%. The spatially averaged $Q/I$ amplitude is about 2.5% at $\mu = 0.1$ and 0.5% at $\mu = 0.5$, in agreement with the results of Trujillo Bueno et al. (2004). The standard deviations ($\sigma$) of the $Q/I$ fluctuations are approximately 0.5% at $\mu = 0.1$ and 0.3% at $\mu = 0.5$. As shown in the corresponding bottom panels of Figure 1, the Stokes $U/I$ signals are very significant, with a typical spatial scale of the fluctuation similar to that of $Q/I$, but with positive and negative values lying between about −1% and 1% at $\mu = 0.5$ (with a $\sigma \approx 0.3\%$) and between −2% and 2% at $\mu = 0.1$ (with a $\sigma \approx 0.7\%$). Such $U/I$ signals are exclusively due to the asymmetry-breaking effects caused by the horizontal atmospheric inhomogeneities, which are quantified by the tensors $J_2^J$ and $J_2^Q$. The spatially averaged $U/I$ amplitudes are not zero, although they are rather small (e.g., $U/I \approx -0.03\%$ at $\mu = 0.5$).

The right panels of Figure 1 show that the $Q/I$ and $U/I$ signals at the solar disk center ($\mu = 1$) are significant and that they have subgranular patterns. In this forward-scattering geometry, both $Q/I$ and $U/I$ have positive and negative values, which are exclusively due to the asymmetry-breaking effects (see eqs. [3] and [4] for $\mu = 1$). In the unmagnetized case of Figure 1, such values vary between −0.6% and 0.8%, approximately, but with most of the signals located between −0.2% and 0.2% (with a $\sigma \approx 0.1\%$). As expected, the spatially averaged $Q/I$ and $U/I$ values at the solar disk center are very small—that is, of the order of 0.001%.

Figure 2 shows results for the $\mu = 0.5$ case as well, but assuming a particularly interesting magnetized model characterized by a horizontally fluctuating microturbulent field with $B = 15$ G at all heights within the solid-line contours of the right panels of Figure 1 (which delineate the granular upflowing regions) and by $B = 300$ G at all heights outside such solid-line contours (which correspond to the downflowing intergranular regions). This model implies saturation of the Hanle effect for the Sr I λ4607 line in the intergranular regions of the photospheric plasma, as suggested by the Hanle-effect investigation of Trujillo Bueno et al. (2004, 2006). The spatially averaged $Q/I$ amplitude is now about 0.3% (instead of the $0.5\%$).
The magnetic sublevels of the upper level of the Sr I λ4607 line without the need of an inclined magnetic field.

Actually, such symmetry-breaking effects produce sizable $U/I$ signals at any on-disk position, with positive and negative values fluctuating across the field of view with an amplitude that increases toward the solar limb. On the other hand, with the exception of the previously mentioned forward-scattering disk-center case, the $Q/I$ signals far away from the solar disk center are instead dominated by the anisotropy of the radiation field and fluctuate around a nonzero mean value that is larger when closer to the solar limb. The local $Q/I$ values are influenced by the symmetry-breaking effects, but the spatially averaged $Q/I$ amplitudes at each $\mu$ position turn out to be similar to those calculated by Trujillo Bueno et al. (2004), which confirms their conclusion on the presence of a significant amount of hidden magnetic energy and (unsigned) magnetic flux in the quiet solar photosphere.

The reported patterns in the fractional linear polarization are of great diagnostic interest because they are sensitive to the thermal, dynamic, and magnetic structure of the quiet solar photosphere. We urge our solar observer colleagues to carry out the proposed observations as soon as possible. While a 1 m telescope with adaptive optics should be sufficient for the particular case of the Sr I λ4607 line, the observation of this type of linear polarization signal in most of the other lines of the second solar spectrum would require a larger aperture solar telescope. The design of the European Solar Telescope (EST) and of the Advanced Technology Solar Telescope (ATST) should incorporate the scientific findings reported in this Letter. To detect and quantify the predicted fluctuations in $Q/I$ and $U/I$ across a two-dimensional field of view would be of fundamental importance to our deciphering the small-scale magnetic activity of our nearest star.

This research has been funded by the Spanish Ministerio de Educación y Ciencia through project AYA2004-05792 and by the National Academy of Sciences of Ukraine through project 1.4.6/7-226B.

5 Note that the typical spatial and temporal scales of the reported $Q/I$ and $U/I$ fluctuations are those of the solar granulation.

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