THE HANLE EFFECT OF Lyα IN A MAGNETOHYDRODYNAMIC MODEL OF THE SOLAR TRANSITION REGION

J. Štepán1,2, J. Trujillo Bueno2,3,4, M. Carlsson5,6, AND J. Leenaarts5,7

1 Astronomical Institute ASCR, Štefánikova 298, 251 65 Ondřejov, Czech Republic
2 Instituto de Astrofísica de Canarias, E-38205 La Laguna, Tenerife, Spain
3 Departamento de Astrofísica, Facultad de Física, Universidad de La Laguna, E-38200 La Laguna, Tenerife, Spain
4 Instituto de Investigaciones Físicas de Canarias, Tenerife, Spain
5 Instituto of Theoretical Astrophysics, University of Oslo, P.O. Box 1029 Blindern, NO-0315 Oslo, Norway
6 Online-only material: color figures

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In order to understand the heating of the solar corona it is crucial to obtain empirical information on the magnetic field in its lower boundary (the transition region). To this end, we need to measure and model the linear polarization produced by scattering processes in strong UV lines, such as the hydrogen Lyα line. The interpretation of the observed Stokes profiles will require taking into account that the outer solar atmosphere is highly structured and dynamic, and that the height of the transition region may well vary from one place in the atmosphere to another. Here, we report on the Lyα scattering polarization signals we have calculated in a realistic model of an enhanced network region, resulting from a state-of-the-art radiation magnetohydrodynamic simulation. This model is characterized by spatially complex variations of the physical quantities at transition region heights. The results of our investigation lead us to emphasize that scattering processes in the upper solar chromosphere should indeed produce measurable linear polarization in Lyα. More importantly, we show that via the Hanle effect the model’s magnetic field produces significant changes in the emergent Q/I and U/I profiles. Therefore, we argue that by measuring the polarization signals produced by scattering processes and the Hanle effect in Lyα and contrasting them with those computed in increasingly realistic atmospheric models, we should be able to decipher the magnetic, thermal, and dynamic structure of the upper chromosphere and transition region of the Sun.

Key words: polarization – radiative transfer – scattering – Sun: chromosphere – Sun: surface magnetism – Sun: transition region

1. INTRODUCTION

In order to understand the heating of the solar corona, it is crucial to obtain empirical information on the strength and orientation of the magnetic field in its lower boundary (the transition region), where over very short distances (≈100 km) the temperature suddenly rises from <105 K to >106 K and the atmospheric plasma changes from partially to practically fully ionized (e.g., Golub & Pasachoff 2010). To this end, we need to measure and model observables sensitive to the magnetic field of the transition region.

In a recent paper, Trujillo Bueno et al. (2011) argued that the hydrogen Lyα line is expected to show measurable scattering polarization when observing the solar disk, and that via the Hanle effect the line-center linear polarization amplitude shows good sensitivity to magnetic field strengths between 10 and 100 G, approximately. These conclusions were reached through detailed radiative transfer calculations in semi-empirical and hydrodynamical models of the solar atmosphere, assuming complete frequency redistribution and neglecting quantum interference between the two upper levels of the Lyα line (see Štepán & Trujillo Bueno 2011 for details on the atomic model and numerical method of solution). As shown by Belluzzi et al. (2012), these last two approximations are suitable for estimating the polarization signals at the core of Lyα, which is the spectral line region where the Hanle effect in Lyα operates.8

The above-mentioned investigations were carried out using one-dimensional (1D) models of the extended solar atmosphere, such as the semi-empirical models of Fontenla et al. (1993) and the hydrodynamical models of Carlsson & Stein (1997). However, both observations (e.g., Vourlidas et al. 2010) and simulations (e.g., Leenaarts et al. 2012) show that the outer solar atmosphere is highly structured and dynamic, departing radically from a uniform, plane-parallel configuration. Thus, the height of the transition region must vary from one place in the atmosphere to another, most probably delineating a highly corrugated surface. It is in this type of spatially complex plasmas where strong transition region lines like Lyα originate. The presence of horizontal atmospheric inhomogeneities in a stellar atmosphere breaks the axial symmetry of the radiation field within the medium, and this type of symmetry breaking may produce changes in the scattering polarization signals that could be confused with those caused by the Hanle effect (e.g., Manso Sainz & Trujillo Bueno 2011; Anusha & Nagendra 2011). It is therefore important to investigate the problem of scattering polarization and the Hanle effect in Lyα using spatially complex models of the outer solar atmosphere, where the physical quantities may vary abruptly not only along the radial direction but also horizontally. To this end, Štepán & Trujillo Bueno (2012; J. Štepán & J. Trujillo Bueno, in preparation) have developed a three-dimensional (3D), multilevel radiative transfer code for doing simulations of the spectral line polarization caused by scattering processes and the Hanle and Zeeman effects within the framework of the quantum theory of polarization described in Landi Degl’Innocenti & Landolfi (2004).

8 Partial frequency redistribution (PRD) and J-state interference can, however, produce large linear polarization signals in the wings of the Q/I profile of Lyα, especially for close-to-the-limb line of sights (see Belluzzi et al. 2012).
This Letter represents a first step toward that goal. Given the complexity of the radiative transfer problem of the Hanle effect in 3D model atmospheres here we start by considering a two-dimensional (2D) model atmosphere characterized by spatially complex variations of the physical quantities at chromospheric and transition region heights, taken from the 3D radiation magnetohydrodynamic (MHD) simulations mentioned below. Of particular interest here is comparing the \( Q/I \) and \( U/I \) profiles computed assuming \( B = 0 \) G at each spatial grid point of the considered MHD atmospheric model with the fractional linear polarization signals calculated taking into account the Hanle effect caused by the model’s magnetic field.

### 2. FORMULATION OF THE RADIATIVE TRANSFER PROBLEM

We have selected a snapshot from a state-of-the-art radiation MHD simulation performed with the Bifrost code (Gudiksen et al. 2011) taking into account non-equilibrium hydrogen ionization. A snapshot from the same simulation (but 30 s earlier in time), which has a magnetic field configuration representative of an enhanced network region, was used by Leenaarts et al. (2012) and we refer the reader to that paper for details on the 3D structure. Figure 1 illustrates the snapshot we have selected from this simulation. The magnetic field has a predominantly bipolar structure, with magnetic field lines connecting two clusters of photospheric magnetic concentrations of opposite polarity and reaching chromospheric and coronal heights. In this Letter, we consider a 2D model atmosphere extracted from this 3D snapshot; its physical quantities are those found within the \( Z-Y \) plane at \( X = 12 \) Mm (see the dashed line in Figure 1). Since the magnetic field lines in this 3D snapshot are approximately perpendicular to such a \( Z-Y \) plane and the temperature between the magnetic patches shows filamentary structure that follows the general orientation of the magnetic field, we believe that the 2D approximation is reasonable for computing the emergent Stokes profiles for lines of sight (LOS) with azimuths \( \chi = 0^\circ \) or \( \chi = 180^\circ \) (i.e., for LOS contained in any \( Z-X \) plane).

The \( \text{Ly}\alpha \) line results from two blended transitions between the ground level of hydrogen, \( 1s^2S_1/2 \), and the \( 2p^2P_1/2 \) and \( 2p^2P_3/2 \) excited levels. The only level that contributes to the scattering polarization and the Hanle effect of \( \text{Ly}\alpha \) is the \( 2p^2P_3/2 \) (e.g., Trujillo Bueno et al. 2011). We have adopted the same atomic data used by Trujillo Bueno et al. (2011) in their 1D investigation, the only difference being that we have used a model atom composed of the above-mentioned levels and the \( 2s^2S_{1/2} \) level whose collisional coupling with the \( P \)-levels may contribute to a slight depolarization of the line. As shown by Štepán & Trujillo Bueno (2011) this is a very suitable atomic model for computing the line-center polarization of \( \text{Ly}\alpha \). We aim at comparing the \( Q/I \) and \( U/I \) profiles computed assuming \( B = 0 \) G at each spatial grid point of the above-mentioned 2D atmospheric model with the fractional linear polarization signals calculated taking into account the Hanle effect caused by the model’s magnetic field. To this end, we have applied the radiative transfer code mentioned in Section 1. As advanced by Štepán & Trujillo Bueno (2012), two novel features of this 3D code for the transfer of polarized radiation are a formal solver based on short characteristics with quadratic Bezier-splines interpolation (which implies a significantly more stable formal solver than those based on the standard parabolic interpolation method) and a highly convergent iterative method based on the nonlinear multigrid method described in Fabiani Bendicho et al. (1997). For the angular integration, we have used Gaussian quadrature for the ray inclinations with respect to the vertical \( Z \)-axis (with seven inclinations per octant) and the trapezoidal rule for the ray azimuth (with five azimuths per octant).

The top panel of Figure 2 shows the spatial variation of the kinetic temperature in the chosen 2D model atmosphere, where it can be clearly seen that the height of the transition region changes drastically from one horizontal location to another.
Figure 2. Physical quantities across the vertical 2D slice defined in Figure 1. From top to bottom: (a) temperature, (b) the fractional anisotropy of the Lyα radiation field (the black contours show the plasma β parameter—that is, the ratio of the gas to the magnetic pressure), (c) magnetic field strength B, (d) inclination of magnetic field with respect to the positive Z-axis, and (e) azimuth of the magnetic field with respect to the positive X-axis. The white line in each panel indicates the height, associated with each horizontal Y-point, where the line-center optical depth is unity along an LOS with \( \mu = 0.3 \), and we point out that it is very similar to that corresponding to other \( \mu \) values. Note that in one-dimensional semi-empirical models the transition region to the coronal temperatures occurs instead at a rather precise height (e.g., at about 2200 km in the FAL-C model), which approximately coincides with the height where the Lyα line-center optical depth is unity along the LOS. In both types of atmospheric models (MHD and semi-empirical) the line-core Lyα radiation originates around such transition region heights.

(A color version of this figure is available in the online journal.)

outlining a highly crumpled surface. The next panel of Figure 2 shows the spatial variation of the fractional anisotropy of the Lyα radiation, \( J_2^2 / J_0^0 \) (see Equations (2) and (3) in Trujillo Bueno et al. 2011), calculated after obtaining with the above-mentioned radiative transfer code the self-consistent solution to the problem of resonance line polarization and the Hanle effect. As shown in this panel, the height variation of \( J_2^2 / J_0^0 \), at most horizontal positions Y, is qualitatively similar to that shown for Lyα in Figure 1 of Trujillo Bueno et al. (2011), which corresponds to the solution of the same non-LTE polarization transfer problem in the semi-empirical model C of Fontenla et al. (1993; hereafter FAL-C model). Note that at most horizontal positions the fractional anisotropy is zero at all photospheric and chromospheric heights, but that it suddenly becomes significant right at the location of the transition region, with larger negative values than in the case of the semi-empirical FAL-C model atmosphere. This is important because of the following two reasons: (1) the corrugated surface that delineates the model’s transition region practically coincides with that corresponding to line-center optical depth unity along the LOS and (2) the line-center amplitude of the \( Q/I \) profile of the Lyα line is approximately proportional to the \( J_2^2 / J_0^0 \) value at such transition region heights (cf. Equation (1) of Trujillo Bueno et al. 2011).

The three extra panels of Figure 2 show the spatial variation of the strength, inclination, and azimuth of the model’s magnetic field. Note that at the crinkled surface that outlines the location of the model’s transition region (which approximately coincides with the height where the Lyα line-center optical depth is unity along the LOS) the strength of the magnetic field varies between a few gauss and 60 G, approximately. Since the Hanle effect in Lyα is mainly sensitive to magnetic strengths between 10 and 100 G (cf. Trujillo Bueno et al. 2011), we should expect
3. THE EMERGENT Q/I AND U/I SIGNALS

The first step needed to compute the emergent Q/I and U/I signals is to obtain, at each spatial point within the chosen model atmosphere, the self-consistent values of the density-matrix elements corresponding to each $j$-level of our 4-level atomic model (i.e., 9 $\rho^K_j$ elements quantifying the overall population of each $j$-level and the population imbalances and coherences among the sublevels of the $2p^2P_3/2$ level). To this end, we have applied the 3D radiative transfer code developed by Štěpán & Trujillo Bueno (2012; J. Štěpán & J. Trujillo Bueno, in preparation) to solve the two following cases: (1) the zero-field reference case, by forcing $B = 0$ G at each spatial grid point in the atmospheric model (top panels) and (2) the Hanle effect case, by taking into account the model’s magnetic field. The general multilevel expressions of the radiative transfer coefficients and of the statistical equilibrium equations corresponding to this so-called NLTE problem of the second kind can be found in Sections 7.2 and 7.13 of Landi Degl’Innocenti & Landolfi (2004).

In Figure 3 we show, for an LOS with $\mu = 0.3$ and azimuth $\chi = 0^\circ$, the emergent Q/I and U/I profiles calculated for each of the above-mentioned two cases. The first important point to emphasize is that the amplitudes of the linear polarization signals are very significant ($\sim 1\%$), both in the absence (top panels) and in the presence (bottom panels) of the model’s magnetic field, and that they show significant spatial variations.

Note that Q/I is always negative and that its amplitude is significantly larger in the zero field case. The fact that U/I ≠ 0 for the $B = 0$ G case (top panels) indicates that the model’s horizontal inhomogeneities (e.g., in temperature and density) are efficient in breaking the axial symmetry of the incident radiation field at each point within the medium. Interestingly enough, both the amplitude and the sign of U/I are significantly modified by the action of the Hanle effect (compare the top and bottom panels), mainly in the central part of the 2D model where the magnetic field strength is significantly larger than in the model’s boundaries (see Figure 2).

4. THE MAGNETIC SENSITIVITY OF THE SPATIALLY AVERAGED Q/I AND U/I SIGNALS

It is also interesting to consider the spatially averaged Q/I and U/I signals, including their sensitivity to the mean magnetic field strength obtained by averaging the magnetic strength at each point of the corrugated surface that defines the spatial location of the model’s transition region. To this end, we have multiplied the strength of the local magnetic field by a scaling factor $0 \leq f \leq 8$. Figure 4 shows the results for an LOS with $\mu = 0.3$.

The dashed red line of Figure 4 shows the magnetic sensitivity of the total fractional linear polarization, $P_L = \sqrt{\langle Q \rangle^2 + \langle U \rangle^2}/\langle I \rangle$, where it can be seen that the model’s magnetic field produces a significant depolarization with respect to the zero-field reference case via the Hanle effect. More interesting is to note that $\langle U \rangle/\langle I \rangle \approx 0$ in the absence of magnetic fields while $\langle U \rangle/\langle I \rangle \approx \pm 1\%$ with the model’s magnetic field (see the black and blue dotted lines). As shown by the solid lines, the Hanle effect of the model’s magnetic field has a significant impact on the $\langle Q \rangle/\langle I \rangle$ amplitude, whose sign remains the same for the two considered LOS azimuths.
Figure 4. \(\langle Q/U, U/I, Q/I\rangle\) and \(P_L = \sqrt{\langle Q\rangle^2 + \langle U\rangle^2}/\langle I\rangle\) spatially averaged amplitudes vs. the mean field strength of the model’s transition region, as discussed in Section 4. The LOS chosen have \(\mu = 0.3\) and azimuths \(\chi = 0^\circ\) (black lines) and \(\chi = 180^\circ\) (blue lines). The vertical green line indicates the mean field strength of the model’s transition region. Other solutions have been obtained by scaling the modulus of the model’s magnetic field with a scaling factor \(0 \leq f \leq 8\). Note that the \(\langle Q/U\rangle\) amplitude corresponding to the zero-field reference case in the chosen 2D model is significantly larger than that found by Trujillo Bueno et al. (2011) in the one-dimensional FAL-C model. (A color version of this figure is available in the online journal.)

5. CONCLUDING COMMENTS

In order to obtain quantitative information on the magnetic field of the upper chromosphere and transition region of the Sun, we need to measure and model the linear polarization caused by scattering processes in some strong resonance lines, such as the hydrogen Ly\(\alpha\) line at 1216 Å. This is because via the Hanle effect such polarization is sensitive to the strength and orientation of the magnetic field expected for the solar transition region plasma (with \(B \lesssim 100\) G). The interpretation of the observed Stokes profiles will require taking into account that the outer solar atmosphere is highly structured and dynamic. For this reason it is important to do numerical simulations of the scattering polarization that is produced in realistic MHD models of the solar atmosphere, paying particular attention to understanding the impact of the model’s magnetic field on the emergent \(Q/I\) and \(U/I\) profiles.

In this Letter, we have made a first step toward that goal by solving the multilevel radiative transfer problem of the scattering polarization and Hanle effect in Ly\(\alpha\) in a 2D snapshot taken from the 3D radiation MHD simulation of an enhanced network region described in Leenaarts et al. (2012). To this end, we applied the 3D radiative transfer code described in Štepán & Trujillo Bueno (2012; J. Štepán & J. Trujillo Bueno, in preparation).

Our model calculations of the line-core \(Q/I\) and \(U/I\) signals at each point on the model’s surface show that the horizontal inhomogeneities of the chosen atmospheric model produce a significant impact on the local scattering polarization amplitudes, and that these linear polarization signals are significantly different in the absence and in the presence of the Hanle effect produced by the model’s magnetic field. Moreover, the spatially averaged \(Q/I\) and \(U/I\) signals also show an interesting sensitivity to the model’s magnetic field. We therefore conclude that by measuring the polarization signals produced by scattering processes and the Hanle effect in Ly\(\alpha\) and contrasting them with those computed in increasingly realistic atmospheric models, we should be able to decipher the magnetic, thermal, and dynamic structure of the upper chromosphere and transition region of the Sun.

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