We present some theoretical predictions concerning the amplitude and magnetic sensitivity of the linear-polarization signals produced by scattering processes in the hydrogen Lyα line of the solar transition region. To this end, we have calculated the atomic-level polarization (population imbalances and quantum coherences) induced by anisotropic radiation pumping in semiempirical and hydrodynamical models of the solar atmosphere, taking into account radiative transfer and the Hanle effect caused by the presence of organized and random magnetic fields. The line-center amplitudes of the emergent linear-polarization signals are found to vary typically between 0.1% and 1%, depending on the scattering geometry and the strength and orientation of the magnetic field. The results shown here encourage the development of UV polarimeters for sounding rockets and space telescopes with the aim of opening up a diagnostic window for magnetic field measurements in the upper chromosphere and transition region of the Sun.

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

1. INTRODUCTION

One of the big challenges of 21st century astrophysics is to understand the magnetism of the Sun, and in doing so, to develop the tools needed for the exploration of the magnetic activity in other types of stars across the Hertzsprung–Russel diagram. A crucial step toward this goal is to decipher the magnetic structure of the upper chromosphere, the key interface region between the underlying (cooler) photosphere and the overlying (hotter) corona where dominance of the physics passes from hydrodynamic to magnetic forces (e.g., the review by Harvey 2006). To this end, we need

1. to identify observables sensitive to the magnetic fields of the upper chromosphere and transition region;
2. to develop suitable diagnostic tools to infer the magnetic field from those observables; and
3. to design and build the telescopes and instrumentation needed for measuring the observables.

The upper chromosphere is indeed a very important part of the Sun because all of the plasma, magnetic field, and energy in the corona and solar wind are supplied through this key boundary region. The observables that contain information on the physical conditions of this region are mainly spectral lines in the ultraviolet (UV) and far-UV (FUV) spectral range, with Lyα being the most prominent line. The intensity profile (i.e., the Stokes $I(\lambda)$ profile) of Lyα and other lines of the Lyman series has been measured on the solar disk by several instruments on board rockets and space-based telescopes (e.g., Roussel-Dupré 1982; Warren et al. 1998). These measurements show that when observed on the solar disk the hydrogen Lyman lines are always in emission, and that the emission originates in the upper chromosphere and transition region. Interestingly, high-resolution Lyα intensity images of quiet-Sun regions taken with the Very high Angular resolution ULtraviolet Telescope (VAULT) sounding rocket show a forest of elongated fibrils suggesting closed magnetic loops in the upper chromosphere (Vourlidas et al. 2010). However, no quantitative information on the magnetic field of the upper solar atmosphere can be obtained from this type of observations because the intensity profile of Lyα and of many other transition region lines is practically insensitive to the strength, inclination, and azimuth of the magnetic field vector.

The only way to obtain quantitative empirical information on the strength and orientation of the magnetic field is through the measurement and interpretation of the polarization that some physical mechanisms introduce in spectral lines. Unfortunately, the familiar Zeeman effect is of little practical interest for the “measurement” of magnetic fields in the upper chromosphere and transition region (except perhaps in sunspots) because the circular polarization (Stokes $V$) scales with the ratio, $R$, between the Zeeman splitting and the Doppler line-width and the linear-polarization (Stokes $Q$ and $U$) scales with $R^2$; this ratio is very small for the UV and FUV lines that originate in the weakly magnetized plasma of the upper solarchromosphere because $R \propto \sqrt{\lambda T}$ (with $\lambda$ being the wavelength, $B$ the magnetic strength, and $T$ the kinetic temperature; see Landi Degl’Innocenti & Landolfi 2004). Fortunately, there is yet another physical mechanism by means of which the magnetic fields of a stellar atmosphere leave fingerprints in the spectral-line polarization: the Hanle effect. The absorption of anisotropic radiation produces atomic-level alignment (i.e., the individual magnetic substates of levels with angular momentum $j \geq 1$ are unevenly populated, in such a way that the populations of sublevels with different values of $|M|$ are different and, moreover, quantum coherences between them may appear). This, in turn, gives rise to linear polarization in the spectral line under consideration (e.g., Trujillo Bueno 2001). The Hanle effect due to the presence of a magnetic field inclined with...
respect to the symmetry axis of the pumping radiation field modifies the atomic-level alignment and the linear polarization of the spectral-line radiation. Approximately, the emergent linear polarization is sensitive to magnetic strengths between 0.2B_H and 5B_H, where B_H = 1.137 × 10^{-7} \text{H}_\text{field}^{2} \text{g} is the critical Hanle field (in G) for which the Zeeman splitting of the line’s level under consideration is similar to its natural width (with H_{\text{field}} being the level’s radiative lifetime, in seconds, and g its Landé factor). Note that B_H ≈ 50 G for Lyα, B_H ≈ 20 G for Lyβ, and B_H ≈ 8 G for Lyγ, and that the magnetic sensitivity provided by the Hanle effect is independent of the Doppler line width.

Each Lyman line results from two blended transitions between a lower level, with j = 1/2, and two upper levels, with j = 1/2 and j = 3/2. Therefore, for each Lyman line the only level that can be aligned and contribute to the emergent linear polarization is the upper level with j = 3/2 (when the hyperfine structure of hydrogen is neglected, which is known to be a good approximation for Lyα). A particularly important question is whether the atomic alignment of the 2p^2P_{3/2} level of Lyα is significant or, in other words, if the Lyα radiation that illuminates the hydrogen atoms of the solar atmosphere is sufficiently anisotropic in the line formation region. Obviously, the anisotropy of the incident Lyα radiation is very significant in the optically thin case of the solar corona observed off-the-limb at large distances above it (e.g., Trujillo Bueno et al. 2005, and more references therein). The key question for us here is, however, whether the Lyα radiation is sufficiently anisotropic within the solar transition region itself, so as to produce there a significant amount of atomic alignment in the 2p^2P_{3/2} level. As mentioned above, the Lyman radiation that we observe when pointing to the solar disk is produced by the plasma of the solar transition region, which is very optically thick at the central wavelength of Lyα. As a matter of fact, the center-to-limb variation (CLV) of the observed Lyα intensity is very small or negligible (e.g., Roussel-Dupré 1982; Curdt et al. 2008), which implies that the intensity of the outgoing radiation (i.e., that propagating outward) shows no significant variation with the heliocentric angle θ. However, this does not mean that the illumination of the transition region atoms is isotropic—which would imply that the scattering polarization in Lyα is zero. As we shall see below, the intensity of the incoming radiation (i.e., that propagating inward) calculated in semiempirical and hydrodynamical models of the solar chromosphere shows significant CLV, so that the hydrogen atoms of the solar transition region must be illuminated by an anisotropic radiation field. The main goal of this Letter is to show that the linear-polarization amplitude of the emergent Lyα radiation is predicted to be significant because of the anisotropy of the incoming radiation and that via the Hanle effect it is sensitive to the magnetic fields expected for the upper chromosphere and transition region of the Sun.

We focus here on Lyα because it is the most intense line of the solar transition region and also because its polarization is practically insensitive to collisional depolarization there, but we point out that linear polarization due to atomic-level alignment is also expected for at least Lyβ and Lyγ.

2. FORMULATION OF THE PROBLEM

We have applied the quantum theory of spectral-line formation described in Chapter 7 of Landi Degl’Innocenti & Landolfi (2004), which treats the scattering line polarization phenomenon as the temporal successor of first-order absorption and re-emission processes, interpreted as statistically inde-

pendent events. This complete frequency redistribution (CRD) approximation is suitable for reaching the objective of this Letter—that is, to estimate the line-center polarization amplitudes in the absence and in the presence of the Hanle effect (e.g., Sampoorna et al. 2010 and more references therein).

The splitting between the 2p^2P_{3/2} and 2p^2P_{3/2} upper levels of Lyα is of the order of 10^{10} s^{-1}, which is much larger than the level’s natural width (of the order of 10^{8} s^{-1}) but much smaller than the line’s Doppler width (of the order of 10^{13} s^{-1}). This justifies neglecting quantum interferences between such two j-levels (see Belluzzi & Trujillo Bueno 2011). The upper level 2p^2P_{3/2}, with Landé factor g = 4/3, is the only level that contributes to the linear polarization of Lyα when its hyperfine splitting is neglected, which as shown by Bommier & Sahal-Brèchot (1982) is a good approximation.

In order to estimate the linear-polarization amplitudes of Lyα we need to take into account radiative transfer effects in models of the solar atmosphere. To this end, we have chosen both the quiet-Sun semiempirical model of Fontenla et al. (1993, hereafter the FAL-C model) and the chromospheric hydrodynamical model of Carlsson & Stein (1997, hereafter the hydrodynamical model). The atomic model we have used includes all the fine-structure levels of the first three n-levels of hydrogen (that is, it includes Lyβ and Hζ, in addition to Lyα). We quantify the excitation state of each j-level by means of the multipolar components of the atomic density matrix, whose self-consistent values at each spatial grid point of the model atmosphere have to be obtained by solving jointly the statistical equilibrium equations for such density-matrix components and the Stokes-vector transfer equation for each of the allowed radiative transitions in the atomic model. To this end, we have applied an efficient and accurate radiative transfer method (see Appendix A of Štěpán & Trujillo Bueno 2011). Isotropic collisions with protons and electrons have also been taken into account, as described in Appendix B of Štěpán & Trujillo Bueno (2011). In particular, the dipolar collisional rates between nearby j-levels (i.e., between levels nlj and n′lj ± 1j′) have been calculated by applying the semiclassical impact approximation theory (e.g., Sahal-Brèchot et al. 1996), while the inelastic collisional rates between the different n-levels were taken from Przybilla & Butler (2004). We have included also the Stark broadening of the hydrogen lines, following Stehlé (1996). With these physical ingredients, our non-LTE syntheses of the hydrogen intensity profiles are in good agreement with those computed by other researchers using more n-levels.

3. THE ANISOTROPY OF THE Lyα RADIATION IN THE SOLAR TRANSITION REGION

In the absence of magnetic fields, the line-center amplitude of the fractional scattering polarization in the Lyman lines can be estimated by applying the following approximate expression (see Trujillo Bueno & Manso Sainz 1999, and note that the 1/\sqrt{2} factor here takes into account that two blended transitions contribute to the intensity profile):

\[
\frac{Q}{I} \approx \frac{1}{\sqrt{2}} (1 - \mu^2) W_2(j, j_0) \frac{J_0^2}{J_0^0},
\]

where \( W_2(j, j_0) = 1/2 \) for the Lyman lines, \( \mu = \cos \theta \) (with \( \theta \) being the heliocentric angle), and \( J_0^2/J_0^0 \) is the fractional anisotropy of the spectral-line radiation calculated at the height in the model atmosphere where the line-center optical depth
is unity along the line of sight (LOS). Therefore, the key quantity that determines the scattering polarization signals we may expect for the Ly\(\alpha\) line when observing the solar disk is \(J_0^0/J_0^0\), where

\[
J_0^0 = \frac{1}{2\sqrt{2}} \int d\nu \int \frac{d\Omega}{4\pi} \phi(\nu, \Omega) I_{\nu,\Omega}
\]

is the familiar frequency-integrated mean intensity (\(\phi(\nu, \Omega)\) being the normalized absorption profile, with \(\nu\) being the frequency and \(\Omega\) the ray direction), and

\[
\frac{J_0^0}{J_0^0} = \sqrt{2} \int d\nu \int \frac{d\Omega}{4\pi} \phi(\nu, \Omega) \times [(3\mu^2 - 1)L_{\nu,\Omega} + 3(\mu^2 - 1)Q_{\nu,\Omega}]
\]

quantifies the anisotropy of the spectral-line radiation that illuminates each point of the astrophysical plasma under consideration.\(^6\) In solar-like atmospheres the first term of Equation (3) plays the dominant role, so \(J_0^0 > 0\) if the incident radiation field is predominantly vertical while \(J_0^0 < 0\) if it is predominantly horizontal. The specific intensity depends on the spatial variation of the corresponding source function component, \(S_{\nu,\Omega}\). If \(S_{\nu,\Omega}\) decreases with height in the solar atmosphere then the outgoing radiation shows limb darkening (i.e., it is predominantly vertical), while the incoming radiation shows limb brightening (i.e., it is predominantly horizontal). It is the magnitude of the vertical gradient of \(S_{\nu,\Omega}\) that determines the sign of \(J_0^0\) (see Figure 4 of Trujillo Bueno 2001). For a constant source function we have \(J_0^0 < 0\), because in this particular case all outgoing rays have the same intensity and we are left only with the (predominantly horizontal) contribution of the incoming radiation.

The left panel of Figure 1 shows the spatial variation of \(J_0^0/J_0^0\) for H\(\alpha\), Ly\(\alpha\), and Ly\(\beta\), calculated in the FAL-C model. Note that the anisotropies of the Lyman lines are practically zero all through the model atmosphere, except in the model’s transition region where they are negative and significant (i.e., of the order of a few percent at the atmospheric heights where the line-center optical depth is unity along the LOS). The right panel of Figure 1 illustrates that in the model’s transition region the Ly\(\alpha\) anisotropy is dominated by the CLV of the incoming radiation.

4. SCATTERING POLARIZATION AND HANLE EFFECT IN Ly\(\alpha\)

The two panels of Figure 2 show the calculated CLV of the emergent \(Q(\lambda)/I(\lambda)\) profile of the Ly\(\alpha\) line (hereafter, \(Q/I\)). The left panel corresponds to the results of our radiative transfer calculations in the semiempirical FAL-C model, while the right panel shows the \(Q/I\) profiles that result from averaging the time-dependent Stokes \(I\) and \(Q\) profiles calculated in the hydrodynamical simulation model of Carlsson & Stein (1997). The variation with \(\mu\) of the line-center amplitude of the \(Q/I\) profile can be easily understood by using Figure 1 (right panel) and Equation (1). Remarkably, the amplitude and shape of the \(Q/I\) profiles calculated in both solar atmospheric models are qualitatively similar; this re-enforces our conclusion that

\(^6\) Note that these are the CRD expressions for \(J_0^K\) (with \(K = 0, 2\)). Partial frequency redistribution expressions for \(J_0^K\) can be found in the paper by Sampoorna et al. (2010), which clarifies that CRD is a suitable approximation for estimating the line-center scattering polarization.
scattering processes in the solar transition region should indeed produce measurable linear-polarization signals in \( \text{Ly}\alpha \). We point out that the transition region starts at a rather precise height in the FAL-C model (i.e., at about 2200 km), while in the hydrodynamical model it fluctuates with time.

We turn now to estimating the sensitivity of the emergent \( \text{Ly}\alpha \) linear polarization to the presence of organized and random magnetic fields in the solar transition region. Since similar conclusions are obtained with the hydrodynamical model, it suffices to show the results of our self-consistent radiative transfer calculations in the FAL-C model atmosphere.

Figure 3 shows the calculated \( Q/I \) and \( U/I \) signals for a LOS with \( \mu = 0.3 \), which implies a distance of about 45″ from the solar limb. Except for the \( B = 0 \) G case (shown in Figure 3 with a gray dotted line for reference), the curves show \( Q/I \) and \( U/I \) for a horizontal (i.e., parallel to the solar surface) magnetic field of 20 G; the field has a fixed orientation given by the azimuth angle written in the figure panels. Note that both \( Q/I \) and \( U/I \) are sensitive to the azimuth of the magnetic field vector: while the \( Q/I \) signal changes but remains always negative, the sign of \( U/I \) also depends on the azimuth value.

In such close-to-the-limb scattering geometry, \( U/I \) would be zero if, instead of having a dominant orientation, the magnetic field azimuth was uniformly distributed within the spatio-temporal resolution element of the observation. However, away from the solar disk center, \( Q/I \) remains sensitive to the magnetic field strength even in such an unfavorable situation. This can be seen clearly in the left panel of Figure 4, which shows how the amplitude of \( Q/I \) signal decreases as the magnetic strength of a random-azimuth horizontal field increases. As seen in this figure, for the scattering geometry of a close-to-the-limb observation (e.g., \( \mu = 0.3 \)), the Hanle effect depolarizes. However, for the forward-scattering geometry of a disk center observation (i.e., a LOS with \( \mu = 1 \)), the Hanle effect of an inclined magnetic field with a given orientation creates linear polarization (see the right panel of Figure 4 and note that in order to be able to detect the presence of a horizontal magnetic field of 30 G in the bulk of the solar transition region the polarimetric sensitivity of the measurement should be at least 0.1%). Therefore, the Hanle effect in \( \text{Ly}\alpha \) can be used to diagnose the magnetic field all over the solar disk (i.e., it is not restricted to an annular region around the solar limb).

5. CONCLUSIONS

Our radiative transfer investigation in semiempirical and hydrodynamical models of the solar atmosphere indicate that the \( \text{Ly}\alpha \) line should show measurable linear-polarization signals when observing the solar disk. Via the Hanle effect the line-center amplitudes turn out to be sensitive to the presence of magnetic fields in the solar transition region, with good sensitivity to field strengths between 10 and 100 G. For such field strengths there is no significant impact of the Zeeman effect on the \( \text{Ly}\alpha \) radiation.

The above-mentioned prediction is based on the same quantum theory that explains the linear-polarization profiles...
The predicted line-center amplitudes of the Lyα scattering polarization are smaller than 1%. Nevertheless, with a moderate aperture telescope they can be measured with a polarimetric sensitivity of 0.1% and a spectral resolution of 0.1 Å by opting for a spatial resolution of the order of 1 arcsec and a temporal resolution of the order of 1 minute (e.g., see the Lyα polarization sounding rocket project outlined in Ishikawa et al. 2011). Information on the thermal and magnetic structure of the solar transition region can be obtained from the observed Q/I and U/I profiles themselves and through detailed radiative transfer simulations in given atmospheric models. Therefore, it would be worthwhile to develop a spectropolarimeter for measuring from space the linear-polarization profiles caused by scattering processes and the Hanle effect in the Lyα line of the solar transition region. Unfortunately, the pioneering Soviet satellite experiment of Stenflo et al. (1980) failed because the optical transmission of the instrument was severely degraded due to in-orbit contamination from the satellite. Such a development would open up a novel diagnostic window for the exploration of the magnetism of the outer solar atmosphere.

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