Spatiotemporal Evolution of Hanle and Zeeman Synthetic Polarization in a Chromospheric Spectral Line

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Abstract
Due to the quick evolution of the solar chromosphere, its magnetic field cannot be inferred reliably without accounting for the temporal variations of its polarized light. This has been broadly overlooked in the modeling and interpretation of the polarization, due to technical problems (e.g., lack of temporal resolution or of time-dependent MHD solar models) and/or because many polarization measurements can apparently be explained without dynamics. Here, we show that the temporal evolution is critical for explaining the spectral-line scattering polarization because of its sensitivity to rapidly varying physical quantities and the possibility of signal cancellations and attenuation during extended time integration. For studying the combined effect of time-varying magnetic fields and kinematics, we solved the 1.5D non-LTE problem of the second kind in time-dependent 3D R-MHD solar models and synthesized the Hanle and Zeeman polarization in forward scattering for the chromospheric \( \lambda 4227 \) line. We find that the quiet-Sun polarization amplitudes depend on the periodicity and spectral coherence of the signal enhancements produced by kinematics, but that substantially larger linear polarization signals should exist all over the solar disk for short integration times. The spectral morphology of the polarization is discussed as a combination of Hanle, Zeeman, partial redistribution and dynamic effects. We give physical references for observations by degrading and characterizing our slit time series in different spatiotemporal resolutions. The implications of our results for the interpretation of the second solar spectrum and for the investigation of the solar atmospheric heatings are discussed.

Key words: polarization – radiative transfer – scattering – shock waves – stars: atmospheres – Sun: chromosphere

1. Introduction
Two 4 m class solar telescopes (EST, Collados et al. 2013; DKIST, Rimmele et al. 2013) with exceptional spectropolarimetric capabilities are being developed at the present moment. They are expected to provide a sensitivity of \( 10^{-4} \) while preserving the spatiotemporal resolution of \( \approx 0\,''1 \times 20 \) s required for following the evolution of the chromospheric spectral-line polarization. Without it, the signals end up being significantly integrated in space, time, and/or wavelength, either intrinsically, by an instrument without enough resolution, or after detection, for increasing the signal-to-noise ratio (S/N) delivered by the spectropolarimeter.

Thus, spatiotemporal integration limits the study of the quiet solar chromosphere. Possible sign cancellations below the resolution element definitely kill the already-faint transversal Zeeman signals produced by the weak chromospheric magnetism. The only alternatives then are scattering signals, which can exist even in the absence of a magnetic field. Atoms scattering polarized light are the closest thing to an ideal in situ detector of plasma properties (with data transponder incorporated), exhibiting large responsiveness to chromospheric magnetic fields by the Hanle effect, but also to the chromospheric temperature and velocity gradients via changes in radiation field anisotropy and atomic polarization (Carlin et al. 2012, 2013). Anisotropic radiation also adds sensitivity to the horizontal inhomogeneities in the plasma when the 3D structure of the radiation field is considered (Manso Sainz & Trujillo Bueno 2011; Štěpán et al. 2015). When by this or another reason the symmetry in the scattering is broken (e.g., by a nonradial magnetic field in forward scattering), the modulation of chromospheric atomic polarization produced by shock waves becomes visible in large and frequent changes in the shape, sign, and amplitude of the emergent profiles (Carlin & Asensio Ramos 2015). Thus, it has been recently pointed out that, in contrast with previous expectations, sign cancellations can also affect the Hanle polarization signatures for current typical resolutions (Carlin & Bianda 2016, hereafter CB16).

Note that the current maximum spatial resolution seems enough for tracking spatial variations of the quiet chromospheric magnetism through scattering Hanle signals (which is yet harder with the transversal Zeeman effect). However, the temporal scales of the chromosphere are significantly shorter than the several minutes that most observations of scattering polarization last. Hence, analyzing a time average, the information contained in the temporal evolution (e.g., continuity and causality of events) is lost, and the comparison with calculations becomes misleading. Furthermore, as chromospheric events can be very fast, they are not statistically well represented in calculations with single MHD snapshots of limited extension. For target resolutions around \( 0\,''1 \times 20 \) s, our calculations support detection of near-ubiquitous scattering polarization signals in the quiet chromosphere once a sensitivity of \( 10^{-4} \) (\( 10^{-3} \) for some spectral lines) is surpassed. This threshold is thus quiet particular, a sort of discrete leap, because crossing it should allow the detection of an almost fully polarized solar disk (including disk-center quiet sun) in several spectral lines. Thus, our simulations try to estimate the polarization that a 4 m class solar telescope might observe when the dynamic signals are measured in their proper timescales. On the other hand, we expect that this work helps to find a way of disentangling the effect of velocities and magnetic fields in the Hanle signals of chromospheric lines. CB16 advanced some of the results, pointing out that a minimal
understanding of the temporal evolution of the polarization is required for determining magnetic fields in dynamic layers, as well as for deciphering the second solar spectrum.

In the present paper we continue studying the Stokes signals of the $\lambda4227$ line (located at 4226.728 Å in air). This paradigmatic spectral line of the second solar spectrum has been widely studied, both observationally and theoretically, over the past 50 years. Some examples are Brückner (1963), Dumont et al. (1973), Stenflo (1974), Dumont et al. (1977), Faurobert-Scholl (1992), Bianda et al. (1998), Holzreuter et al. (2005), Sampoorna et al. (2009), Anusha et al. (2010), Bianda et al. (2011), and Supriya et al. (2014). Our work differentiates from these studies in that we consider a time series of realistic 3D radiation-MHD models as input atmospheres, the effect of spatiotemporal integration and macroscopic vertical motions, the forward-scattering Hanle and Zeeman signals, and the whole Stokes vector. We call Ca I $\lambda4227$ a reference line because the quantification of dynamic effects in its spectral core gives useful physical insights for unpuzzling other scattering signals forming at similar heights but with richer atomic structure, such as the Na I D lines. $\lambda4227$ seems indeed ideal for this purpose because it is a chromospheric spectral line with minimal quantum complexity: normal Zeeman triplet, no hyperfine structure, no lower-level polarization. Furthermore, its large forward-scattering polarization signals in all Stokes parameters permit us to explore the lower chromosphere at and around disk center, which avoids the more complex interpretation of line-of-sight (LOS) superposition effects at the solar limb (see introduction of Carlin 2015).

After presenting our results (Section 3), we continue with some discussions (Section 4). The key in Section 4 is that the degeneracy in the solar signals can lead to close fits with simulations, implying, however, wrong physical inferences, and that this is avoided with larger spatiotemporal resolutions and a precise characterization of the effect of chromospheric dynamics (i.e., time evolution of macroscopic motions and heatings) in the polarization.

2. Synthesis of the Polarization Signals

2.1. The Atmospheric Model

The input for our calculations is a time-dependent MHD simulation computed with the Bifrost code (Gudiksen et al. 2011) considering nonequilibrium hydrogen ionization. It emulates a bipolar magnetic structure with network properties and its quiet-Sun surroundings, having an average unsigned magnetic field strength of 48 G in the model photosphere. The spatial physical domain covers a horizontal extension of $24 \times 24$ Mm$^2$ with a horizontal resolution of 48 km and a vertical resolution of 19 km in photosphere and chromosphere. The temporal evolution lasts 15 minutes of solar time with a resolution of 10 s. For more details see Carlsson et al. (2016). Figure 1 shows the slit-like region of $\approx 0.5 \times 33^\prime$ (it has a certain width) that was selected in the models for our calculations.

2.2. Calculation Procedure

We developed a pipeline of programs that processes data levels in independent steps. In step 1 the MHD simulation (data level 1) is read and transformed for multidimensional visualization and plotting (data level 2). Having selected the region where the radiative transfer is to be carried out, the inputs (data level 3) for the RH 1.5D code (Uitenbroek 2001; Pereira & Uitenbroek 2015) are created. Such a code is set to solve the non-LTE (NLTE) ionization balance between Ca I and Ca II using a 20-level atomic model that accounts for the lower transitions of Ca I and the ground level of Ca II with 19 continuum transitions and 17 line transitions. Photoionization and inelastic collisional excitations/de-excitations due to electrons are considered for all levels. The inclusion of Caii is negligible for computing the Ca I populations because the
population of the former starts to be significant from heights above the upper chromosphere, while Ca I forms entirely below the middle chromosphere. Thus, in the solar models considered, Ca II provides the entire reservoir population.

The calculation of atomic populations with RH was done considering partial redistribution (Leenaarts et al. 2012). Comparing the results in partial redistribution (PRD) and complete redistribution (CRD), we have seen that this affects (but not dramatically) the atomic populations. The reason is simply that the NLTE mean radiation field is slightly affected by the increased PRD emissivity.

The atomic populations resulting for the levels of the $\lambda 4227$ line and the MHD quantities are the input (data level 4) for Handy$^\dagger$ (HANle DYnamic Polarized Radiation In Moving Envelopes). This code solves the NLTE radiative transfer problem of the second kind (Landi Degl’Innocenti & Landolfi 2004, Section 14.1, hereafter LL04), processing each time step independently and applying the 1.5D (or column-by-column) approximation to each pixel of the slit. Thus, horizontal inhomogeneities and horizontal velocity gradients do not contribute to the nonlocal part of the problem (the radiation field). The NLTE iteration provides the converged values of the components of the statistical density matrix, which accounts for atomic populations, atomic polarization, and quantum coherences in magnetic energy sublevels. The emergent radiative transfer performed with the converged atomic density matrix is fully realistic in forward scattering (disk-center LOS). The local physics (collisions, Zeeman and Hanle effects) is properly treated. This approach allows us to investigate the effect of vertical variations in the MHD quantities and provides spatiotemporal continuity to the results.

The calculations with polarization were done in the regime of CRD. This is justified because PRD effects are negligible in the line core and in forward-scattering, meaning a range of $\mu = [0.89, 1]$ for the $\lambda 4227$ line (e.g., Dumont et al. 1973; Anusha et al. 2011). However, our comparisons with observations suggest that the agreement with CRD seems confined to a more restricted disk-center area, roughly to $\mu \in [0.96, 1]$ (see Section 3.8).

In any case, the $\lambda 4227$ line core is not blended or affected by the weak spectral lines forming in its proximities (Lites 1974). Continuum polarization is generally very small and is also minimized in forward scattering.

For this paper the pure Zeeman effect (no atomic polarization, no quantum coherences) in $Q, U, \, V$ was calculated separately from the Hanle signals in order to compare both contributions to the LP. Namely, the equations solved here are the statistical equilibrium equations given by a suitable combination of Equations (7.2.a) and (7.101) of LL04 under the impact approximation and the assumption of isotropy for depolarizing and inelastic collisions (Lamb & Ter Haar 1971), and the radiative transfer equation for an instantaneously stationary radiation field with propagation matrix given by Equations (7.2.b) (Hanle regime) and by Equations (9.4), (9.7), and (9.10) (Zeeman regime) of LL04 neglecting stimulated emission. The optical profiles entering in the propagation matrix are calculated using a damping parameter that includes the dominant contributions of radiative ($A_{\text{dil}} = 2.18 \times 10^8$) and Van der Waals ($\gamma_{\text{vdw}} = 1.7 \times 10^{-8}$, $a_{\text{vdw}} = 0.389$) broadening (Stenflo 1974; Faurobert-Scholl 1992). The resolution of the wavelength and angular grids are automatically set by adapting them to the level of kinematics affecting the radiative transfer.

When integrating in angle (e.g., to obtain the radiation field tensor), we use a Gaussian quadrature whose minimal number of points in inclination angles is defined by the rule explained in Figure 2.

The final step of the calculations tries to facilitate the analysis. It involves the characterization of the Stokes signals and of the physical quantities related to polarization at the region of formation of each wavelength. These metrics (data level 5) allow us to correlate detailed quantities in multiple dimensions for understanding possible patterns that can lead to better diagnosis in time-dependent atmospheres. All data levels are structured following NetCDF4 standards. All our calculations were done for microturbulent velocity $v_{\text{micro}} = 0 \text{ km s}^{-1}$ and $v_{\text{micro}} = 2 \text{ km s}^{-1}$.

2.3. Minor Modifications to RH 1.5D

In the presence of shock waves the numerical convergence of some radiative transfer codes with polarization is usually not guaranteed because a mere Doppler shift can make the elements of the propagation matrix of consecutive points in the optical path differ abruptly in amplitude at a given wavelength. Physically, this is an obstacle especially in the low chromosphere, on one hand because there the ratio between the vertical velocity gradients and the thermal broadening is usually larger than at other heights (by combination of shock waves and cool plasma pockets), and on the other hand because in the low chromosphere the frequent meeting between upward shocks and plasma falling back fast from previous waves produces larger velocity gradients. Numerically, the problem is that some formal solvers of the radiative transfer equation become unstable in such situations unless a very fine grid is used. Instead of modifying the formal solver used by RH, we have assured stability and convergence modifying RH 1.5D for redistributing, when necessary, the atmospheric grid points toward those heights where certain proxies to opacity change more abruptly. Combining this method$^2$ with an eventual better grid resolution, all columns converge.

Other minor modifications done to RH for developing this work include (i) calculation of heights of formation for all wavelengths at additional optical depths in the transition of interest, (ii) the possibility of redefining the cutting atmospheric points using optical depth and hydrogen density thresholds, and (iii) the possibility of increasing the number of spatial grid points in run time.

3. Results

3.1. Magnetic References in Semiamprirical Models

Before considering MHD models, we calculated the emergent forward-scattering polarization in an FALC model (Fontenla et al. 1993) with a constant ad hoc magnetic field. We did it for all possible magnetic field azimuths and inclinations, and for strengths between 10 and 130 G (Hanle saturation for Ca I $\lambda 4227$) every 10 G. Representing in the Poincaré sphere ($Q, \, U, \, V$ space) the amplitude of each polarization profile for each case, we obtain an extension of a Hanle diagram, what we call a Poincaré diagram (Figure 3). This representation has not been used before for characterizing

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$^1$ http://www.unidata.ucar.edu/software/netcdf/

$^2$ To be eventually published in a separate publication.
the Hanle and Zeeman effects in a solar atmosphere, but it seems quite illustrative in this regard. The additional Stokes $V$ dimension in Poincaré diagrams partially breaks the degeneracy of polarization with magnetic field orientation. This representation gives a more compact and clear view of the limiting polarization values for a given spectral line and LOS.

We find that at disk center the total LP of $\lambda 4227$ in semiempirical models is always in the range of 0.1%–0.5% for any magnetic field inclination $\theta_B \in [17^\circ, 163^\circ]$ and any azimuth if the magnetic field is lower than 50 G. Most magnetic fields affecting the line core in the time-dependent simulations are between this value and 10 G, hence very close to the optimal value that maximizes the Hanle effect and that is given by the upper-level Hanle critical field of 20–25 G.

As shown by Figure 3, the previous minimum of LP = 0.1%, given by near-vertical magnetic fields, is also produced at Van Vleck inclinations: $\theta_B = [54^\circ73, 125^\circ27]$. Therefore, predominantly horizontal fields, with inclinations contained between those Van Vleck angles, cannot make $Q/I$, $U/I$, and $V/I$ be below 0.1% in large areas simultaneously. If this happens observing a line whose S/N is expected to be good, we assume that this is because collisions and/or dynamic effects are canceling the polarization. In particular, a total LP < 0.1% over large solar areas suggests that dynamics might be producing sign cancellations below the temporal resolution element (we will discuss this later). Here dynamics also refers to situations with a time-varying magnetic field in the resolution element. For instance, our simulations show that emerging cool bubbles seem to make the magnetic field inclination oscillate between the horizontal and near-Van-Vleck angles (see Figure 4 around $x = 18^\circ$ and $x = 23^\circ$).

If the maximum values of the measured LP are above the semiempirical (static) reference of 0.5%, it is necessary to assume that the amplifications introduced by macroscopic motions along time are significant, occurring at certain wavelengths with enough persistence (spectral coherence) and/or strength during the exposure time.

**Figure 2.** In the presence of large vertical velocities the error in the Gaussian quadratures used to calculate the radiation field tensor is larger for those rays whose $\xi = [\mu \cdot \Delta \mu]$ is maximum (with $\mu = \cos(\theta_k)$, and $\Delta \mu = \mu_{k+1} - \mu_k$, for a ray $k$). Continuous curves above show this quantity for different quadrature grids with number of points labeled by their cut with the horizontal axis. In order to give a rule for the number of angular points, we take the $\Delta \mu$ at that maximum $\xi$ as the limiting worst case. We find that such $\Delta \mu$ is $\approx 1/N_{\mu} + 0.003$ for any number of points. On the other hand, as $\Delta \mu$ must be $< 1/V_{\text{Max}}$ ($V_{\text{Max}}$ being the maximum Doppler velocity in the atmosphere), the recipe turns out to be $N_{\mu} \geq 2.1 \cdot V_{\text{Max}}$. This rule is only applied when giving a number larger than a safe minimum of 13 points per quadrant in inclination.

**Figure 3.** Poincaré diagram for Ca I $\lambda 4227$, $\mu = 1$, FALC atmosphere, constant ad hoc $B = 50$ G. The black line connects all points with $\lambda_B - \chi = 90^\circ$ ($\chi$ sets the direction of $Q > 0$ in space).

**Figure 4.** MHD quantities at $\tau = 1$ for the line-center wavelength in each time step and length coordinate in the slit. Velocity shocks are here exposed by removing at each time step the average offset velocity due to the 5-minute oscillations (see its effect in the height of formation). The vertical velocity map is on the left.

### 3.2. Formation Region

Significant variations in the height of formation are normal in chromospheric lines. In the models considered the region of formation ($0.1 < \tau < 10$) of the minimum line-core intensity of $\lambda 4227$ oscillates between $0.7$ Mm $< z < 1.5$ Mm, tending to contain the coolest atmospheric patches located just above the small-scale magnetic canopy (see Figure 1, right panel). A first reason for this is that neutral calcium density peaks in cool volumes. A second one is that in forward scattering the height of formation is the lowest possible. Due to the proximity to the small-scale magnetic canopy, the region of $\tau = 1$ at the line
core is normally filled by near-horizontal magnetic fields at any time, which maximizes the forward-scattering Hanle effect. Such a magnetic canopy separates the photosphere and chromosphere (see Figure 1) and seems to play a role in the heating of the chromosphere (e.g., Goodman 1996). Also in these layers the incipient shock waves start to act significantly in the line core. In semiempirical models this corresponds to heights between the temperature minimum and the first temperature bump. A similar scenario is expected for chromospheric polarization signals of other neutral atomic elements.

3.3. Instantaneous Polarization Features

The temporal variations of the synthetic polarization profiles along the slit are large. The LP has almost-universal, sudden, and conspicuous increments (in absolute value) moving rapidly along the spatial direction. An inspection of the instantaneous slit profiles in the temporal series (e.g., in CB16, Figure 5 in this paper, or Figure 3 in Carlin 2016) reveals the following.

1. The spatial exclusion (or complementarity) of linear and circular polarization due to their different sensitivities to transversal and longitudinal magnetic fields. An additional reason is that the formation region, though corrugated, is roughly parallel to the surface, hence crossing suddenly the vertical magnetic lines emerging from magnetic patches. In observations at disk center, sizable $V/I$ and line-core LP are sometimes cospatial.

2. A weak (negligible) transversal Zeeman effect along the whole slit, though $\lambda 4227$ forms in the low chromosphere. Hence, all relevant features in $Q$ and $U$ are Hanle polarization. As the field is relatively weak, the Zeeman profiles only have $\sigma$ components. They usually enclose the spectral Hanle core, but sometimes they lie in it, due to height-dependent longitudinal motions (see Figure 5). Each $\sigma$ component is narrow (even with microturbulence) and can be, each of them, antisymmetric, hence having opposite signs in their small spectral width. When this happens, the variable Doppler shifts existing during the time integration can easily weaken the final LP Zeeman amplitudes.

3. The correlation between spectrally broad strong circular polarization, heating signatures in intensity, and stronger vertical magnetic fields. Spectrally broad $V/I$ profiles can be understood as a consequence of the weak-field approximation for Stokes $V$ (being proportional to the wavelength derivative of the intensity) when the intensity profile has conspicuous peaks outside the core and the longitudinal magnetic field is strong enough. At disk center, the formation region of the $\lambda 4227$ near-core peaks in intensity is already sub-chromospheric; hence, the heatings creating such intensity excesses are not due to compressing shock waves.

4. The dynamic modulation of Hanle signals by vertical gradients of velocity. The general response of the scattering LP signals to velocity gradients does not require lower-level alignment (as it did for Ca II IR triplet lines in Carlin et al. 2013) if the upper level can instead harbor it.

5. The strong instantaneous amplitudes of the forward-scattering $\lambda 4227$ polarization. They are larger than in observations presumably because they are calculated with spatial and temporal resolution, which minimizes cancellations. This should mean that magnetic field diagnosis via Hanle in the bulk of the chromosphere is not physically limited by too weak signals at disk center.

6. The presence of antisymmetric LP profiles, without a dominant sign (see Figures 2 and 3 of CB16 or Figure 6 here). Hence, the Hanle core can in principle have any shape, and not necessarily a single line-core lobe as usually thought. The origins of such antisymmetric LP profiles are a variation of magnetic field azimuth along the LOS and/or the modulation of the height-dependent radiation field anisotropy by vertical velocity gradients.

7. The different instantaneous shapes of $Q/I$ and $U/I$ at a given same location. Due to the physical symmetry at disk center in 1.5D, one would expect $Q/I$ and $U/I$ with similar (normalized) shapes. This fails when the magnetic field azimuth changes along $0.1 < \tau_\lambda < 10$, such that the height maximizing $Q/I$ (i.e., where $\chi_B = 0, \pm 90, 180$) in a wavelength $\lambda$ is different than the height for $U/I$ (peaking in $\chi_B = \pm 45, \pm 135$). Thus, the magnetic field can narrow down the formation region of the polarization to specific layers. This also means that the difference in shape between both normalized profiles quantifies the magnetic field azimuth gradient along the LOS.

3.4. Polarization without Microturbulence

Large-scale photospheric oscillations introduce an offset Doppler shift with a period of 5 minutes that simultaneously affects all spectra along the slit. Comparing signals calculated without ad hoc microturbulent velocity (see Figure 6) in opposite instants in which the maximum 5-minute-period Doppler shifts are maximum, it is seen that such shifts are larger than half the broadening of the LP profile. When the chromospheric Doppler shifts (e.g., due to shock waves) are added, the result is LP profiles with reduced overlapping along time (compare upper LP panels of Figure 6). This weakens and shapes the integrated LP signals, due to their lack of reinforcement during the exposure time. Thus, integrating 1′/4 and several minutes (5 and 15 minutes in lower left and right panels, respectively), we find synthetic LP signals that are weaker than those in the observations of Figure 7. The maximum absolute LP value in the 15-minute integration is...
0.11%, which is four times weaker than in the observations and three times weaker than in the calculations with $\nu_{\text{micro}} = 2 \text{ km s}^{-1}$. Let us note that a distinctive point of the observed scattering polarization is to have significant amplitudes after long exposures; hence, it is important to emulate this. Furthermore, without microturbulence all the Stokes components are too narrow.

### 3.5. Polarization with Microturbulence

The observational constraints in broadening and amplitudes mentioned before are reasonably achieved when $\nu_{\text{micro}} = 2 \text{ km s}^{-1}$ (see Figure 8). The significant improvement provided by the microturbulence points out that the lower chromosphere of the models is too cool (particularly around the coolest locations, where this line tends to form). The agreement in morphology is now also remarkable. A chain of nearly-symmetric LP rings\(^3\) appear after 5 minutes of integration, when the maximum integrated amplitudes coincide with the observed ones. Such an agreement between the left two panels of Figure 8 and the observations results of adding up hundreds

\(^3\)These LP features resemble rings in the wavelength–space plane because the core Hanle signal is surrounded in space and wavelength by nearly symmetric peaks of opposite sign.
of very different instantaneous Stokes profiles (those in a bin of 1°4 and 5 minutes).

An equivalent example for longer exposure times (15 minutes) is given by the second pair of panels in the same figure. The maximum amplitudes are yet close to the observed ones, as required in Section 3.4. Additionally, there is attenuation over significant extensions of the slits, with amplitudes well below the minimum reference defined in semiempirical models in Section 3.1. This can help to explain the “noise pools” found in observations of scattering polarization. For instance, the very small (noisy) $V/I$, $Q/I$, and $U/I$ over the lowest part of the slit in the observation of Figure 7 are surely not produced by a particular magnetic field orientation or by collisional processes, which should act in other close internetwork (IN) regions as well. Hence, dynamics might be the reason. Middle panels of Figure 9 show how dynamics and time integration attenuate up to a factor of 20 our synthetic observations in relation to the maximum time-resolved signal in the same panels. Comparing with other locations of the slit with less attenuation, we found that strong reductions are produced when the temporal evolution of the signals loses periodicity after a certain time, such that the pattern is not reinforced over long temporal scales. For instance, this happens where LP rings appear.

As in the observations, the $V/I$ profile with microturbulence has a central spectral gap with near-zero amplitude when magnetic fields are vertical. The maximum $V/I$ amplitudes suggest that the temporal scales are correct for the quantities and heights creating circular polarization. Averaging the two peaks of the profiles, we find $[2.16 \pm (-1.85)]/2 \approx 2\%$ and $[0.84 \pm (-0.82)]/2 \approx 0.83\%$ (for the first and fifth strong $V/I$ patches in Figure 6) versus $[0.96 \pm (-0.84)]/2 = 0.9\%$ (for our 15-minute integration synthetic signals). Such an agreement is remarkable because the instantaneous $V/I$ profiles are completely different from the integrated ones (see lowest rightmost panel in Figure 9). This should be considered when interpreting observations of the longitudinal Zeeman effect because it implies that longitudinal magnetic fields inferred from observations without temporal resolution might be significantly weaker than the true ones.

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**Figure 7.** Zimpol@IRSOL observation in $\mu = 0.94$ (middle panels) and corresponding SDO images (lateral panels). The polarization color bars are saturated to ±1% and ±0.4%. The strongest $V/I$ signals are always associated with the network, while the weaker ones correspond to the weak photospheric magnetic elements inside the IN. Zooming in on the intensity, one can see that there is a certain correlation between the strength of the LP rings and shorter-scale spatial intensity variations of higher contrast.

**Figure 8.** Unresolved LP with $\nu_{\text{micro}} = 2$ km s$^{-1}$ and spatial resolution of 1°4. First two panels: LP after 5-minute integration. Last two panels: LP after 15-minute integration. The action of microturbulence allows us to have measurable amplitudes after long exposures.
Building the fractional quantities. Upper panels: more active shortscale dynamics and LP rings. That the synthetic LP instantaneous Stokes profile is the same as before, but in a pixel with a more vertical and intense magnetic field. The Astrophysical Journal, 2017 July 1 (Carlin & Bianda)

\[ \Delta x = 15^\prime, \Delta t = 20 \text{ s}. \]  

\[ \text{Middle panels: } \Delta x = 15^\prime, \Delta t = 15 \text{ minutes in a pixel with predominantly horizontal magnetic field in the low chromosphere during the integration. Lower panels: same as before, but in a pixel with a more vertical and intense magnetic field.} \]

As the calculations with \( v_{\text{macro}} = 2 \text{ km s}^{-1} \) seem to represent better the Sun, only this case is considered in the following.

### 3.6. Emulating a Longer Slit

By repeating blocks of intensity and LP profiles (\( Q/I \) and \( U/I \) indistinctly) along space, Figure 10 emulates a slit with the same length as in our observations. The second panel shows the synthetic intensity integrated over 15 minutes. Stokes \( I/I \), has intensity variations (strips) along the spatial direction whose small scales are compatible with the observed 30-minute average intensity in Figure 7. In the latter figure one has to zoom in a bit to see the less contrasted strips (obtaining synthetic intensity strips with a similar low contrast is just a matter of adding the effect of the stray light in the telescope). The intensity strips are more evident toward the wings and seem to be due to sound waves altering temperature. In the simulations, they have more variability and contrast in weakly magnetized patches of the IN because there the plasma alternate periodically between lower and higher temperatures, which increases emissivity and modulates the damping parameter shaping the near core. The synthetic intensity strips tend to disappear with increases emissivity and modulates the damping parameter shaping periodically between lower and higher temperatures, which correlates with increased temperature and reduced vertical gradients of velocity in Figure 4. Zooming in on the intensity in Figure 7, we have the impression that there is a certain correlation between the strips and the presence of LP rings in \( Q/I \) or \( U/I \). This suggests a relation between more active shortscale dynamics and LP rings.

On the other hand, the rightmost panel of Figure 10 shows that the synthetic LP (\( Q/I \) and \( U/I \) repeated in space) integrated over the 15-minute series is spatially different from that in the 30-minute observations in Figure 7.

For shorter integration times, the spatial lengths of the synthetic LP rings are at least a factor of 4 smaller than in observations. The integration time needed for reproducing their line-core amplitudes is also significantly smaller (5 minutes) than the 30 minutes of the observations. In CB16 we tried to explain these differences in terms of (i) the combination of Hanle effect, kinematics, and lack of resolution, which are effects contained in our simulations; (ii) the transversal Zeeman effect, which shows negligible contribution in our simulations; and (iii) PRD effects, not considered by our calculations because in forward scattering they play no role, but possibly affecting the observations that were not taken exactly at \( \mu = 1 \). These factors behave differently in the two parts of the LP rings (the core and the near-core sign reversals surrounding it); hence, they contribute differently to explain both parts. We will now present additional information that can help to clarify the reason of the differences in scale, starting with the contribution of the line core.

#### 3.7. On the Core of the LP Rings

The length of the LP rings is set by the spatial change of sign in the very line core. If the change was more frequent in space, the number of rings in the slit would be larger and their scale shorter. The maximum possible amplitudes of the synthetic and solar LP rings can be large (compared to the maximum reference values of semiempirical models; see Section 3.1) and occur at line center, not in the sign reversals.

In observations, the LP rings are interconnected by single-lobe signals (forming a chain of rings in IN areas). Similar structures appear in our simulations close to the intermittent emergence of photospheric magnetic elements that are associated with small-scale oscillating chromospheric fields. Figure 4 shows this at the level of the chromosphere. There, a regular emergence of cool plasma bubbles (see temperature panel around \( x = 17^\prime \) and \( x = 22^\prime \) between 0 and 8 minutes) develops into more periodic chromospheric shocks at stable locations. The temperature in these locations shows post-shock rarefaction volumes, i.e., cool bubbles, that are periodic and look more rounded in these spacetime diagrams. The magnetic field inclination, azimuth, and strength oscillate at such positions. The inclination oscillates between horizontal and near-Van-Vleck angles, exposing opposite polarities for \( x = 17^\prime \) and \( x = 22^\prime \) in Figure 4. In between those locations, the chromospheric magnetic field is always close to horizontal. The single-lobe signals linking the LP rings vary in location around such middle locations after integrating in time (Figure 8). The LP rings disappear after those 8 minutes, when the repetitive pattern produced by the waves ends.

This picture presents some agreements with the observations. To have a glimpse of what happens below the temporal resolution element of the ZIMPOL observations (Ramelli et al. 2010), we have inspected the corresponding time evolution of the Solar Dynamics Observatory (SDO) photospheric images (see one snapshot in Figure 7). We find that the link between adjacent LP rings lays between groups of photospheric magnetic elements that appear and disappear around the slit during the exposure time. This leaves a faint residue in the integrated chromospheric \( V/I \) signals: see in Figure 7 the two weak and blurred IN \( V/I \) signals with opposite polarities around \( x \approx 170^\prime \). This residual circular polarization is faint because the emergent magnetic elements, being intermittent, are not there during the
whole exposure time. In our simulations the chromospheric \( \frac{V}{I} \) trace of similar weak magnetic elements fades away easily with exposure time too. In summary, the magnetic elements create small field loops that reach the low chromosphere horizontally where the polarity of \( \frac{V}{I} \) changes. They also seem to be related with the change of sign connecting two LP rings.

### 3.8. On the Sign Reversals of the LP

The origin of the sign reversal at the outer part of the LP rings is not clear because they lay in intermediate wavelengths where all plausible physical effects seem possible.

A transversal Zeeman scenario might seem reasonable for explaining them because significant sigma Zeeman components can be produced by a magnetic field increasing rapidly downward from the formation heights of the Hanle core. But several things point out the contrary. First, the observed LP rings have sizes compatible with the IN patches (\( \approx 20^{\circ}-100^{\circ} \)). This would imply large-scale magnetic fields acting in the IN at the level of the short-scale canopy. Namely, this would mean that large-scale organized field lines (rooted in the network, we presume) with significant chromospheric strengths (\( \gtrsim 100 \) G) are overlying the IN magnetic canopy after their expansion from the network photosphere to the low IN chromosphere. This is incompatible with the current view of an IN permeated by weak short-scale fields and with the simulations. In the simulation, the slit is located very close to a network-like patch (see Figure 1), but even so, the transversal Zeeman signals are roughly of order of magnitude weaker than Hanle. Furthermore, as explained in Section 3.3, larger time integration easily weakens the sigma components even more. Finally, the presence of symmetric sign reversals enclosing the core in the observations is sometimes uncorrelated with the kind of magnetic structures (network or IN) generating it. Hence, the transversal Zeeman effect can be ruled out.

Note that just a sign reversal in the variation with height of the radiation field anisotropy cannot explain the two observed near-symmetric sign reversals enclosing the LP core. As we expand now, there are several reasons, related to how chromospheric motions modify the anisotropy and its impact in the polarization. On one hand, there are effects controlling the sign reversals in the resolved LP profiles: first, the modulation of the anisotropy exerted by vertical velocity gradients can make the LP profiles antisymmetric in low-chromosphere spectral lines (second row, right panel of Figure 7 of Carlin et al. 2012); second, the negative part of the anisotropy tends to disappear with increasing vertical gradients of the source function, e.g., with temperature gradients or in shock waves (Figure 4 of Trujillo Bueno 2001; Carlin et al. 2013); third, when the anisotropy stratification has both negative and positive regions, the dominance of each part in the LP profiles varies significantly owing to the compression/expansion of the formation region around shock fronts (Figure 5.3 of Carlin et al. 2013); fourth, the microturbulent velocity tends to “erase” the near-core sign reversals of LP; and fifth, the Hanle effect of a magnetic field azimuth varying with height can also produce a sign reversal in LP (see last point in Section 3.3), at least around disk center, where the solar-limb polarization offset is weak. The net combination of these effects varies with the spectral line and during the shock’s emergence, but the theoretical trend in the chromospheric lines that we have studied is to destroy the sign reversals in resolved LP profiles. Thus, while antisymmetries (only one sign reversal in the LP core) are possible and asymmetries are everywhere in Figure 10. Spatial pile of synthetic profiles filling the length of the observational slit. First two panels: intensity profiles with full spatiotemporal resolution and after integrating for 15 minutes. Last two panels: same, but for \( Q/I \). Actually, to avoid repetition, the instantaneous panels were composed piling several slits of different time steps, while the averaged slits where obtained by mere repetition along the space of the average profiles. Similarly, the average \( Q/I \) panel is a pile of \( Q/I \) and \( U/I \) average slits.

our simulations, it is very rare to get simultaneous sign reversals on both sides of the core. However, if on top of that we analyze the unresolved LP profiles resulting from such a situation, we find that dynamics can mimic quasi-symmetric sign reversals owing to the combination of instantaneous anisotropy-driven modulations of Hanle signals that are quasi-synchronized with Doppler shifts and integrated in space and time (Carlin & Bianda 2016). The middle panels of Figure 7 show how the instantaneous LP profiles (in gray) tend frequently to group in a sort of Zeeman \( \pi-\sigma \) configuration. Hence, the same feature that was deleted by motions in resolved signals is recreated in the integrated LP when time evolution is included. We refer to this whole situation as the “dynamic Hanle” scenario.

Thus, we are left with two explanations for the symmetric sign reversals: dynamic Hanle and PRD. We try now to discriminate their relative influence by paying attention to the different locations of the PRD and Hanle peaks. To show this, we have applied Principal Component Analysis (PCA; e.g., Rees et al. 2000; Skumanich & López Ariste 2002; Martínez González et al. 2008) to observations of Ca I \( \lambda4227 \) done with ZIMPOL at IRSOL. We considered 450 \( Q/I \) profiles in several lines of sight (\( \mu \in [0.9, 0.96] \)) including profiles with PRD effects around the core. Thus, we obtained the first three PCA eigenvectors (eigenprofiles; see Figure 11), representing 95% of the variance of the data. They are ordered (E1, E2, E3) by the amount of statistical variance that each one explains (size of the projections of the observed data set in each eigenvector). The amplitudes of the eigenprofiles are unimportant; only shape matters. In the Appendix (Figure 14), the eigenprofiles are used to reconstruct some observed profiles.
It is known that the first PCA eigenvector (E1) typically represents the average of the data (Skumanich & López Ariste 2002), in our case mostly affected by instrumental offsets and hence unimportant. In our analysis the second eigenvector (E2) is capturing the PRD wings and separating them from the line CRD core, which is represented by the third eigenvector (E3) and dominated by Hanle and dynamics. PCA allows this separation because the contributions of dynamic Hanle and PRD are maximized at layers that behave very differently (chromosphere and subchromospheric layers). As this happens consistently in all pixels, both physical mechanisms produce statistically uncorrelated changes in the observed profiles, so that PCA gets to separate them in eigenvectors. The PRD wings of E2 have a far-wing maximum and also a near-core minimum that we assign to the sign reversals discussed here. The action of macroscopic motions appears in the asymmetry of both E2 and E3. This gives explicit evidence of the influence of macroscopic motions in observed PRD features, as advanced in Carlin & Bianda (2016). Therefore, it might be important to consider the action of dynamics when studying the PRD polarization features of the second solar spectrum, especially when the PRD wings form in the chromosphere.

Note that the PRD minima of the eigenprofiles are broader and more separated than the minima produced by dynamic Hanle. Thus, the PCA analysis suggests that the dynamic Hanle signature is in better agreement with the width and location of the LP rings in observations. PCA does not explain the large spatial scale of the LP rings.

Inspecting Figure 4 of Trujillo Bueno (2011), we have detected $Q/I$ and $U/I$ rings in quiet-Sun observations of another lower-chromosphere line: Ca II λ8498. In the same figure, the corresponding LP profiles of the λ8542 and λ8662 lines, which belong to the same triplet but form higher, exhibit slit patterns without rings. Instead, they are more like “squared” blocks along the spatial direction of the slit, most of them of single sign. This suggests that in observations of low temporal resolution the LP rings are favored by particular conditions of the lower chromosphere and that the kinematic of upper layers somehow reduces their contrast and oval shapes. As PRD is expected to be particularly negligible in λ8498 (Uitenbroek 1989), this supports the influence of Hanle and dynamics in the LP rings.

Our conclusion is that both dynamics and PRD contribute to the near-core sign reversals, either because PRD itself is affected by dynamics at the very base of the chromosphere or at least because Hanle dynamics and PRD signatures, though forming at different heights, overlap in wavelength in each time step.

### 3.9. Polarization Time Series

The study of the temporal evolution leads to significant insights about the way the solar chromosphere generates scattering polarization. First, it exposes the effect of dynamics, hence giving the possibility of discriminating them to measure chromospheric magnetic fields. Second, it avoids the large degeneracy of integrated signals, which can clarify the origin of the anomalies found in the second solar spectrum.

Figure 12 shows spatiotemporal maps of fractional polarization at the wavelength of the absolute maximum of the profiles. This gives an estimation of the polarization structures that one may aim at observing with the S/N and spatiotemporal resolution of different ground solar facilities (see caption of the figure5): Irsol telescope (lower panels), Gregor (second group of panels from below), and DKIST-EST class telescope (third group of panels from below). The resolution of the top panels is close to that of our calculations.

These maps support the existence of a sensitivity threshold, mentioned in the introduction, above which most of the (now hidden) scattering polarization signals should appear “all at once” because the spatiotemporal scales of chromospheric dynamics are resolved.

Panels in Figure 13 quantify and characterize the variation of the polarization amplitudes with the resolution. Note the different behavior for linear and circular polarization. $Q/I$ and $U/I$ are more sensitive to the temporal evolution of the atmosphere than $V/I$. Independently of the spatial resolution, the first 3 minutes of evolution produce the largest decay of LP, while such decay is mild and almost linear in time for $V/I$.

### 4. Discussion

#### 4.1. Hanle Diagnosis and Polarization Anomalies

Our results show how the solar scattering polarization can depend strongly on the evolution of the chromosphere. Note that despite the fact that polarization amplitudes can decrease significantly with integration time (Figure 13), a given short interval with favorable dynamics and magnetic fields can still restore the integrated LP to maximum values. This is so because the instantaneous signals are intrinsically large for chromospheric kinematics and magnetic fields and because a measurement is an integration, not an average.

The spectral coherence of the polarization during the exposure time matters. Assuming a typical period of $\approx 3$
Figure 12. Time evolution of the slit Stokes vector for several resolutions. From top to bottom: $[\Delta x, \Delta t] = [0', 2, 10 \text{ s}], [0', 4, 60 \text{ s}], [0', 4, 180 \text{ s}], [1', 4, 60 \text{ s}]$. The polarization (intensity) values were chosen in the maximum (minimum) of the spectral profile at each location. Color bars are common; the one for $V/I$ is logarithmic.
minutes for the chromospheric evolution, we obtained reduced LP amplitudes of the order of $\approx 1\%$ after that time (see panel of $\text{LP}_{99.5}$ in Figure 13). This net one-period variation depends on the balance between the kinematic amplification of polarization due to the anisotropic Doppler brightenings (Carlin et al. 2012), the lack of spectral coherence along time (set by thermal broadening, Doppler shifts, and the phase between photosphere and chromosphere waves; see CB16), and the cancellations of LP due to transfer effects along the emergent rays. If the evolution minimizes the fades in a single period and/or maximizes the amplifications with sufficient regularity and spectral coherence over several periods, significant signals can be measured after long exposures. The opposite situation can explain unexpectedly small signals in quiet-Sun locations where semiempirical models predict LP well above the detection limit (see Section 3.1). Thus, other spectral lines and solar regions will have their corresponding Figure 13. We discuss here the evolution of the magnetic field vector too. Its chromospheric inclination can change during the emergence of shock-driven plasma bubbles. This diminishes the LP intermittently, hence reducing amplitudes after 15 minutes of integration (compare amplitudes in 12 Mm $< x < 20$ Mm and in $x > 20$ Mm in the rightmost panel of Figure 7). Through these mechanisms, dynamics increases the range of possible LP amplitudes.

This means that the systematic overlooking of kinematics and time evolution has falsified the previous interpretations of chromospheric Hanle polarization. Curiously, such a “static” approach appeals because both the lack of resolution in the observations and the lack of kinematics in scattering calculations compensate each other within the uncertainties that could be explained with Hanle depolarization. Indeed, the maximum observed polarization amplitudes of several spectral lines agree with the maximum theoretical amplitudes given by semiempirical, and hence static, models of the chromosphere. This assertion is quite precise for the core of the CaI $\lambda$4227 line because the maximum disk-center total fractional LP amplitudes for any $B < 150$ G are always between 0.4% and 0.5% (see Section 3.1), very close to the observed maximum of 0.6%. In other lines or situations without such an agreement between theory and observations, the differences have been associated to Hanle-depolarizing magnetic field inclinations, excluding the challenging anomalous excesses of line-core polarization in certain chromospheric lines (Landi Degl’Innocenti 1998; Stenflo et al. 2000). Our results point out that such difficult cases are precisely showing the limitations of the static approach. The presence of shock waves is sufficient for obtaining instantaneous polarization enhancements of up to one order of magnitude with respect to calculations in static or to temporally unresolved observations. Joining this with a coherent (constructive) dynamics during long exposures, it is possible to explain the excesses of polarization in the second solar spectrum. This favorable situation should be more frequent at the limb, where the anomalous signals appear. There, the height-dependent radiation anisotropy tends to be mapped always in its positive part and the LOS Doppler shifts produced by the emergent waves are minimized, so the spectral LP enhancements are more easily coherent and hence reinforced.

The analysis and interpretation of the second solar spectrum require a new paradigm in which the origin of the scattering signals (the symphony) has to be explained as the result of an atomic system (the instrument) instantaneously reacting to the solar atmosphere (the playing musician). A key remark is that the observed solar polarization is strongly determined by the temporal, geometrical, and spectral variation of the illumination that the scatterers receive, which is ultimately controlled by relative motions around them. Thus, polarization signals can have both large variability and degeneracy; hence, we need a way to systematically expose, group, or constrain this broad range of possibilities. Can we do this with semiempirical models? Are MHD models enough?

4.2. About Semiempirical Models and Heatings

The fact that semiempirical models do not always explain the observed polarization is known (e.g., Smitha et al. 2014; Supriya et al. 2014), but the reasons have not been specified.
The dynamic effects affecting the scattering polarization cannot be reproduced by semiempirical models because they do not depend on time and treat macroscopic kinematics as ad hoc microturbulence velocity. Dynamic effects cannot be modeled by macroturbulence either, because it just changes the shape of the emergent signals but not the polarization properties of the media, similarly to what happens with the velocity-free approximation (Carlin et al. 2013).

The effect of dynamics is more important as we increase resolution. The microturbulent motions parameterized in semiempirical models act as effective Doppler shifts in the profiles when considering resolved observations or MHD simulations. In other words, the dynamic ratio (Doppler velocity in Doppler units),

\[ \xi(s) = \frac{v_{\text{res}}}{v_{\text{unres}}} = \frac{v_{\Omega}}{\sqrt{v^2_{\text{thermal}} + v^2_{\text{micro}}}}, \]

which controls the modulation of anisotropy and LP, increases with resolution because the microturbulent velocity \(v_{\text{micro}}\) passes to be accounted for in the numerator as resolved macroscopic velocity \(v_{\text{res}} = v_{\Omega}\) along the optical path “s” of each ray \(\Omega\). Note that unresolved velocities are both thermal and microturbulent, but only the latter gives a pool of motions that can act as effective Doppler shifts with increased resolution.

Larger \(\xi\) usually implies larger instantaneous LP amplifications, but, depending on the evolution of the thermal broadening (heatings) and kinematics, it can also ease cancellations after temporal integrations, due to sign mixing and spectral incoherence. Thus, not only does microturbulence compensate broadening (lack of heating), but it is also encoded in the LP amplitudes (Section 3.5). This happens through changes in the radiation field anisotropy perceived by the scatterer but also in the amount of atomic population that is pumped to the upper level. For instance, consider a scatterer in the coolest solar layers. A broader absorption profile (larger microturbulence) allows it to capture more pumping light (even without motions) that otherwise would be screened by the even broader profiles sandwiching the region of the temperature minimum. In summary, cooler plasma means scattering polarization more sensitive to kinematics and heatings. Therefore, the shape, width, and amplitude of polarization profiles are a strong test/constraint for the models, even with time integration. This and the current lack of understanding on the distribution of solar chromospheric heatings mean that the choice of microturbulence in calculations of polarization has larger relevance than usually believed.

The fact that the chromospheric temperatures in the MHD models are cooler than in the Sun (Leenaarts et al. 2009) motivated the MHD simulations with higher resolutions considered here. But larger broadenings are still needed. Extra broadening might come from further-increased resolutions in the MHD calculation. However, we think that this will not improve the fit with the observations because the LP profiles would then be narrower and have larger velocities, hence more sensitive to the distribution of motions and prone to loose spectral coherence. This would bring a more efficient cancellation of LP (as in our results without microturbulence), worsening the agreement with observations. Thus, larger temperatures should come from purely thermal sources \(v_{\text{thermal}}\), not from unresolved motions.

Solving the chromospheric and coronal heating problems requires us to understand how the heating sources are distributed in space and time in the solar plasma. Remarkably, this problem could be studied using spectral lines such as \(\lambda 4227\), whose line core forms in the lower chromosphere. There, with minimum temperatures, small variations in temperature become more notable than at the transition region or corona, at least in regard to scattering polarization.

4.3. Three-dimensional Effects

Though in some areas of the disk center the calculations in 1.5D and in 3D seem to give similar results (Štěpán & Trujillo Bueno 2016), the 1.5D approximation does not contain the effect of horizontal velocity gradients or of horizontal inhomogeneities. The goal of the following discussion is to point out some subtleties related with the relative strength of each polarizing effect.

The first one is that 3D effects in the solar polarization may be controlled by dynamics instead of by “plasma inhomogeneities” (spatial lumps of temperature and density). The net pumping radiation at a given scattering point is affected by two contributions: one given by the anisotropic radiation coming from other points in an inhomogeneous but static atmosphere, and another one modulating the former when velocities act in the radiative transfer connecting each point with the scatterer.

Namely, differential velocities all over the formation region (seen by the scatterer) create opacity-changing Doppler shifts along the pumping rays that change the radiation created by the inhomogeneities. In particular, the distribution of horizontal kinematics is, as we develop now, essential for understanding 3D effects because it easily sculpts the effective horizontal radiation field.

The second idea follows. What happens in an atmosphere without preferred horizontal directions? Here the light converging horizontally in each plasma element is affected, at each point of a long optical path, by randomly organized horizontal velocity gradients. This can approximate a net cancellation of the positive and negative azimuth-dependent radiation field components. In this way their contribution to the atomic polarization can be largely exceeded by the combined contributions of (1) the ever-present and comparatively strong vertical gradients driven by shock waves and gravity, which are geometrically “organized,” and (2) the limb brightening/darkening. The 1.5D approximation considers both; hence, if horizontal motions had such an isotropizing effect, the fractional LP in 1.5D would approach the 3D results in larger quiet-Sun areas. In this “dynamic” physical limit, disorganized horizontal velocity gradients minimize the azimuthal anisotropy of the radiation created by inhomogeneities. Thus, though being an opposite situation to that of a 1.5D atmosphere (limit without horizontal gradients/inhomogeneities), both situations let atomic polarization be driven by the vertical stratification of plasma properties. The solar atmosphere is somewhere between these two conceptual limits.

The last subtlety to mention has to do with the fact that 3D solar models are of relatively recent apparition. This implies that their chromospheric horizontal velocity fields lack observational feedback and should be expected to fail at reproducing the limb.

\[ \text{This azimuthal isotropization of the field should be more effective the larger the horizontal extension of the formation region and the less organized are the horizontal velocity gradients.} \]
intensity of chromospheric lines. Contrarily to the “observationally tuned” vertical velocities (Carlsson & Stein 1997), which are basically guided by shock waves and gravity, the less investigated horizontal velocity (gradients) should furthermore depend on the distribution and scales of the magnetic fields in the models. Adding this to the indirect sensitivity that the LP has on temperature through kinematics (recall Section 4.2), we conclude that the differences between 3D and 1.5D calculations might be quite influenced by ingredients of the models that require improvement.

We show the relevance of these ideas commenting on two of the few papers existing on this topic. The key is that the influence of the 3D radiation field on the Hanle polarization has been posed since the beginning in terms of inhomogeneities, and not in terms of velocity gradients. The initial conclusions in this regard were obtained by Manso Sainz & Trujillo Bueno (2011) with an analytical/numerical study approaching the problem in the static regime. In more recent numerical studies the action of 3D velocities in the polarization is included, but the contributions of vertical and horizontal velocity gradients are not separated. As the effects of horizontal velocity gradients and inhomogeneities are in turn blended, it is also unknown how large their relative contributions are to the differences between 1.5D and 3D calculations. Consider, for instance, Figure 3 of Stépán & Trujillo Bueno (2016), which points out that the Hanle effect at disk center tends to depolarize when it is accompanied by other symmetry breaking effect, as happens in the well-known case of the solar limb. The figure also confirms that macroscopic motions are yet an efficient polarizing source for the spectral line considered (as known from 1D simulations of the Ca II IR triplet; Carlin et al. 2013). However, it is unknown whether the polarization introduced by velocity in that figure is due to the horizontal or to the vertical velocity gradients already considered in 1D calculations. This matters not only for comparing with 1D calculations but also because horizontal velocity gradients can potentially compensate and exceed the polarization created by horizontal inhomogeneities (as explained in previous paragraphs). Thus, the dominant symmetry breaking and polarizing effect at disk center could not be the inhomogeneities, as always affirmed, but the horizontal velocity gradients. Hence, we think that is key quantifying the sensitivity of such results to the model horizontal distribution of velocity gradients, which also can help detach the conclusions from the eventual lack of realism in them. Finally, it should also be noted that when those radiative transfer simulations do not add microturbulent velocity, they use the temperature distribution of MHD models that are known to represent a chromosphere cooler than the solar one. Thus, as temperature influences significantly the effect of the velocities in the LP (see Section 4.2), the relative strength of the polarizing effects discussed here might change accordingly.

In summary, horizontal velocity gradients compete with other physical mechanisms, such as inhomogeneities and the Hanle effect, for polarizing and depolarizing the light; hence, we need to explicitly quantify whether they are relevant for inferring magnetic fields with the Hanle effect. We also need to find theoretical and observational methods for discriminating the Hanle effect. Temporal evolution might help toward this aim, which motivated the present paper. Another possibility is to explore the concept of Hanle PILs (Carlin & Asensio Ramos 2015): as in saturation the Hanle effect always nullifies the polarization for particular magnetic field orientations, it creates an ever-present spatial fingerprint of the magnetic field topology in polarization maps.

5. Conclusions

Considering the radiation-MHD simulation of Carlsson et al. (2016), we have simulated the temporal evolution of the spectral-line polarization of the Ca I $\lambda$4227 line in forward scattering, including the Hanle and Zeeman effects.

We find that the large forward-scattering amplitudes of the $\lambda$4227 line are accentuated by its formation region, which is in the temperature minimum and close to the short-scale IN canopy of horizontal magnetic fields. This maximizes the impact of macroscopic motions in the LP and the Hanle effect, respectively. Without the amplification of polarization produced by dynamics, the effect of temporal integration in current observations would make it impossible to detect the scattering polarization signals of this line in the disk center.

At least the strong spectral lines forming in the lower chromosphere are expected to show the largest sensitivity to kinematics and atmospheric heatings in LP. Hence, they offer a possible test bench for understanding the distribution of chromospheric heatings through the scattering polarization. However, where the evolution of dynamics has no sufficient spectral and temporal coherence, the cancellation of signals can make them undetectable. Thus, the evolution of dynamics might be key for explaining the polarization profiles and perhaps the eventual absence of polarization in large areas.

Our calculations indicate that the measurement of polarization time series with exposure times below 1 minute should be of great help for Hanle diagnosis. In the Ca I $\lambda$4227 line, spatial resolutions as large as 0.4 seem enough to detect the Hanle structures of the chromosphere as soon as time resolution is achieved.

The discrimination of Hanle, Zeeman, and PRD effects in the generation of LP rings could not be completely clarified here, but the situation was exposed in better detail, presenting several clues that can guide deeper investigations. The near-core region of the LP profiles is challenging because all possible effects overlap.

It seems necessary to revisit those studies of the second solar spectrum where a formal comparison between theory and observations has been done without accounting for the effect of kinematics and time evolution.

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Appendix

In Figure 14 we show an example of some random observed profiles of Ca I $\lambda$4227 that have been reconstructed using the first three PCA eigenvectors of our database.
Figure 14. Example of some random observed profiles of Ca I λ4227 (black line) that have been reconstructed (blue line) using the first three PCA eigenvectors of our database.

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