New Diagnostic Windows on the Weak Magnetism of the Solar Atmosphere

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Abstract. This article considers some unfamiliar phenomena and subtle physical mechanisms whose understanding and theoretical modeling may help us to investigate the weak magnetism of the extended solar atmosphere. Of particular interest are the Hanle effect in forward scattering at disk center, the existence of 'zero field' dichroism in the solar atmosphere, the fact that vertical magnetic fields enhance the scattering polarization in the Na I D$_2$ line, the "hidden face" of the Hanle effect in molecular lines, and the Hanle effect in solar chromospheric spicules.

1. A useful formula for understanding observations of scattering polarization in spectral lines

My intention in this paper is to consider that regime in which the linear polarization signatures are governed by scattering processes and the Hanle effect, while the circular polarization is mainly the result of the longitudinal Zeeman effect.\(^1\) In such a regime, the radiative transfer equations for the Stokes parameters simplify as indicated by Eqs. (55)–(58) of Trujillo Bueno (2003a). Starting from such transfer equations it is easy to show that the emergent fractional polarization for the Stokes parameter $X$ ($Q$, $U$ or $V$) is approximately given by

$$\frac{X}{I} \approx \frac{\varepsilon_X}{\varepsilon_I} - \frac{\eta_X}{\eta_I},$$

where the components of the emission vector $(\varepsilon_I, \varepsilon_X)$ and those of the absorption matrix $(\eta_I, \eta_X)$ have to be evaluated at the point in the stellar atmosphere where the optical depth $\tau_I = \int \eta_I ds$ along the line of sight is $\tau_I \approx 1$.\(^2\) It is important to note that the first contribution of Eq. (1) stems from the emission process,
while the second one from differential absorption of polarization components (i.e., dichroism). With obvious notation

$$\left( \frac{Q}{I} \right)_{\text{line}} \approx \frac{\epsilon_I^l}{\epsilon_I^l + \epsilon_Q^l} \frac{\epsilon_Q^l}{\epsilon_I^l + \eta_I^l} \frac{\eta_I^l}{\eta_I^l},$$

(2)

where the sub-index 'line' refers to the line contribution to $Q/I$, but taking into account that there is also a background continuum (i.e., the terms $\epsilon_I^l$ and $\eta_I^l$). For the limiting case of a very strong line (i.e., $\epsilon_I^l \gg \epsilon_Q^l$ and $\eta_I^l \gg \eta_I^l$) the fractional polarization at the line core can be written simply as

$$\left( \frac{Q}{I} \right)_{\text{line}} \approx \frac{\epsilon_Q^l}{\epsilon_I^l} \frac{\eta_I^l}{\eta_I^l}.$$  

(3)

In general, the expressions for $(\epsilon_I^l, \epsilon_Q^l)$ and $(\eta_I^l, \eta_Q^l)$ are very complicated (see, e.g., Eqs. (28)–(30) in Trujillo Bueno 2003a, which correspond to the case of a line transition without hyperfine structure). Fortunately, there are situations of practical interest for which such expressions simplify considerably because the quantum coherences ($\rho_U^2$ and $\rho^2_I$) between the magnetic substates pertaining to each level of the line transition under consideration turn out to vanish. Under such circumstances, the expressions given by Eqs. (28)–(30) of Trujillo Bueno (2003a) drastically simplify to give $\epsilon_U^l = \eta_U^l \approx 0$, while $\epsilon_Q^l$ and $\eta_Q^l$ turn out to be simply proportional to the atomic alignment coefficient ($\rho^2_D$) of the upper and lower level of the transition, respectively. Note that $\rho^2_D(J)$ quantifies the degree of population imbalance between the magnetic substates pertaining to the $J$-level. Interestingly, the following two cases satisfy these requirements.

Case A results when the quantization axis of total angular momentum is chosen along the symmetry axis of the pumping radiation field (e.g., along the stellar radius vector through the observed point for a one-dimensional stellar atmosphere model). In this case, one has to assume that the medium is unmagnetized or, for example, that the magnetic field is everywhere microturbulent and isotropically distributed with mixed magnetic polarities within very small spatial scales (i.e., below the photon mean-free path).

Case B corresponds to that of a stellar atmosphere permeated by a deterministic magnetic field with a fixed inclination and azimuth. The magnetic strength must be high enough for the lower-level and upper-level coherences to vanish in the magnetic field reference frame (i.e., that in which the quantization axis of total angular momentum is chosen along the magnetic field vector itself). This case is nothing but the so-called saturated Hanle-effect regime.

For each of such two cases, a very useful formula can be derived which can be applied to estimate the emergent fractional polarization at the core of a strong spectral line for an observation along the line of sight specified by $\mu = \cos \theta$, with

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2 Literally, the word ‘dichroism’ means two coloured. In fact, the term ‘dichroism’ originally referred to crystals that simply appeared to be differently coloured when viewed along different axes. But the effect is much clearer when different directions of polarization are used in viewing the crystals. In some cases, one component of the light is absorbed (the crystal is more or less opaque to it) whereas it may be quite transparent to the other component. We thus have a selective absorption.
\( \theta \) the angle between the chosen quantization axis for total angular momentum and the line of sight (cf. Trujillo Bueno 1999; 2001): \[ Q/I \approx \frac{3}{2\sqrt{2}}(1 - \mu^2)[\mathcal{W} \sigma_0^2(\text{up}) - \mathcal{Z} \sigma_0^2(\text{low})], \] 

where \( \sigma_0^2 = \rho_0^2/\rho_0^0 \) quantifies the fractional atomic alignment or degree of population imbalance of the upper or lower level of the line transition under consideration, while \( \mathcal{W} \) and \( \mathcal{Z} \) are numerical factors which depend on the quantum numbers of the transition (e.g., \( \mathcal{W} = \mathcal{Z} = -1/2 \) for a transition with \( J_l = J_u = 1 \)). \(^5\)

In Eq. (4) the \( \sigma_0^2 \) values are those corresponding to the atmospheric height where the optical depth is unity along the line of sight. It is very important to note that in option A of Eq. (4) the "\( \mu \)" parameter is \( \mu = \mu_R \) (i.e., the cosine of the angle between the solar radius vector through the observed point and the line of sight), while in option B "\( \mu \)" is \( \mu = \mu_B \) (i.e., the cosine of the angle between the magnetic field vector itself and the line of sight). This simple formula for \( Q/I \) shows clearly that the fractional polarization produced by scattering processes in a given spectral line has in general two contributions: one from the fractional alignment of the upper-level (\( \sigma_0^2(\text{u}) \)) and an extra one from the fractional alignment of the lower level (\( \sigma_0^2(\text{l}) \)).

2. The Hanle effect at disk center

In the presence of an inclined magnetic field that breaks the symmetry of the scattering polarization problem at solar disk center, forward scattering processes can produce linear polarization signatures in spectral lines. In this case, the linear polarization is created by the Hanle effect, something that can be understood by reasoning within the framework of the classical oscillator model for the Hanle effect (see section 2.2 of Trujillo Bueno 2001). Interestingly, this can also be understood by considering the above-mentioned case B of Eq. (4). To see this, assume that there is a sufficiently strong magnetic field parallel to the solar surface and choose the quantization axis of total angular momentum along the magnetic field vector itself. As a result, \( \mu = \mu_B = 0 \) in Eq. (4) for a disk center observation, which shows that the mere presence of population imbalances in the upper and/or the lower level of the spectral line under consideration produces a non-zero linear polarization signal (see Fig. 1).

An interesting observational demonstration of the operation of the Hanle effect at the solar disk center was obtained by Trujillo Bueno et al. (2002a) via spectropolarimetric observations of solar coronal filaments in the He I 10830 Å multiplet. The linear polarization detected in the 'blue' component of this multiplet (i.e., that with \( J_l = 1 \) and \( J_u = 0 \)) demonstrated the operation of the lower-level Hanle effect at the solar disk center, while that measured in the 'red' blended component (with the same \( J_l = 1 \), but with \( J_{u2} = 1 \) and \( J_{u1} = 2 \))

\(^4\)In this expression, I have chosen the reference direction for \( Q > 0 \) along the line perpendicular to the stellar radius vector through the observed point.

\(^5\)Note that \( \mathcal{W} = w_{J_u J_l}^{(2)} \) and \( \mathcal{Z} = w_{J_l J_u}^{(2)} \), where \( w_{J_1 J_2}^{(2)} \) is the symbol introduced by Landi Degl’Innocenti (1984).
Figure 1. Illustration of the emergent polarization that results from $90^\circ$ and from forward scattering events in the presence of a magnetic field parallel to the solar surface. The left panel refers to a resonance line with $J_l = 0$ and $J_u = 1$, while the right panel to a spectral line with $J_l = 1$ and $J_u = 0$. Therefore, in the left panel the observed linear polarization is caused by selective emission, while in the right panel the only mechanism that can produce linear polarization is selective absorption. For this reason the observer at position “1” in the r.h.s. panel sees that the light scattered at $90^\circ$ by the weakly-magnetized and optically-thin plasma is virtually unpolarized.

showed an additional contribution caused by the upper-level Hanle effect (see Fig. 4 in Trujillo Bueno et al. 2002a). Note that the mere detection of linear polarization at the solar disk center implies the presence of an inclined magnetic field whose azimuth is being partially resolved. The azimuth $\chi_B$ of the magnetic field vector can be inferred directly from the observations by finding the reference direction for $Q > 0$ that minimizes Stokes-$U$.\footnote{There is a $90^\circ$ ambiguity that can be avoided if one is able to know whether or not the field inclination ($\theta_B$) is larger than Van Vleck’s angle ($54.73^\circ$). Thus, if the He i 10830 Å multiplet is in the saturation regime (e.g., $B > 10$ G) and $\theta_B > 54.73$, then $\chi_B$ coincides with the reference direction that minimizing Stokes-$U$ gives $Q > 0$ in the ‘red line’ and $Q < 0$ in the ‘blue line’. However, if $0 < \theta_B < 54.73$ we have $Q < 0$ in the ‘red line’ and $Q > 0$ in the ‘blue line’.}

In my opinion, there are many other opportunities for investigating ‘horizontal’ magnetic fields via the Hanle effect in forward scattering at the center of the solar disk. For instance, the magnetic field of sunspot penumbrae should allow the Hanle effect to create a measurable forward scattering polarization signal in the $H_\alpha$ line.\footnote{It is also of interest to mention that during this workshop Stenflo (2003) reported the detection of a narrow linear polarization peak in the Ca i 4227 Å line at the solar disk center.}

3. ‘Zero-field’ dichroism in the solar chromosphere

Are the ground and metastable atomic levels significantly polarized in the ‘quiet’ regions of the solar chromosphere and photosphere? Among the many spectral
lines of the second solar spectrum whose linear polarization has been considered ‘enigmatic’ (see Stenflo et al. 2000), let us select here the infrared triplet of ionized calcium in order to demonstrate cleanly that the mysterious polarization is caused by ‘zero-field’ dichroism. This conclusion is particularly important because it implies that there exist significant population imbalances between the Zeeman substates pertaining to each of the two metastable lower-levels of the Ca II IR triplet (i.e., the levels $^2D_{3/2}$ and $^2D_{5/2}$). This triplet is particularly interesting, mainly because the fractional linear polarization ($Q/I$) expected for the 8662 Å line was zero, while the observations of Stenflo et al. (2000) showed a sizable line-core peak with $Q/I \approx 0.12\%$. The 8662 Å line was thought to be intrinsically unpolarizable because its upper level cannot carry any atomic alignment, given that its total angular momentum is $J_u = 1/2$ and calcium has no hyperfine structure splitting.

According to Eq. (4), since $W = 0$ and $Z = 1/\sqrt{2}$ for the 8662 Å line, the explanation of its enigmatic polarization must be the presence of a significant amount of atomic polarization in its long-lived lower-level, which produces differential absorption of polarization components. Manso Sainz & Trujillo Bueno (2003) have demonstrated quantitatively that this is actually the case in the ‘quiet’ solar chromosphere (see Fig. 2). Interestingly, by comparing the observed fractional polarization amplitudes in such IR lines of ionized calcium, we may hope to investigate empirically whether or not milligauss fields in the ‘quiet’ solar chromosphere have a sizable filling factor (Trujillo Bueno & Manso Sainz 2002; see also Section 4 of Trujillo Bueno 2003b).

### 3.1. The enigmatic linear polarization of the Na I D$_1$ line

In spite of what Steven Weinberg said in a TV interview and of Landi Degl'Innocenti’s (1998) letter in Nature, we must admit that the linear polarization peak observed by Stenflo & Keller (1997) in the core of the D$_1$ line still remains enigmatic. The main reason to consider it as truly enigmatic is because of the observational fact, emphasized by Stenflo (2003) during this workshop, that the $Q/I$ shape observed with ZIMPOL on the solar disk is a symmetric peak with a sizable amplitude that, at $\mu_R = 0.05$, was found to be about 4 times smaller than that corresponding to the D$_2$ line, while theoretical modeling based on the last scattering approximation shows that in the absence of magnetic fields the Stokes Q profile of the D$_1$ line is antisymmetric, with an amplitude that is 40 times smaller than that of the D$_2$ line when a model atom with the levels $^3S_{1/2}$, $^3P_{1/2}$ and $^3P_{3/2}$ is used (Trujillo Bueno et al. 2002b).

Nevertheless, over the last few years we have learned a great deal about the true physical mechanisms that control the atomic polarization of the hyperfine structure (HFS) components of the ground-level $S_{1/2}$ of neutral sodium and of

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8The same has been demonstrated also for other ‘enigmatic’ lines of the ‘second solar spectrum’, like the three Mg I b-lines or those of multiplet No. 3 of Ca I (see Trujillo Bueno 1999; 2001).

9Several of us have learned from Rob Rutten that he said the following: “It is a great human comfort to look at a distant star and to realize that the light that reaches our eyes contains the Na I D-lines, the same sodium lines that produce our yellow street lighting, and that we understand exactly how these lines are formed. The sodium atoms in that faraway star obey physical laws that we know and understand in great detail. Isn’t that wonderful!”
Figure 2. Emergent fractional polarization of the Ca II IR triplet at $\mu_R = 0.1$ in the FAL-C semi-empirical model of the solar atmosphere (see Fontenla, Avrett & Loeser 1993) taking into account the influence of ‘zero-field’ dichroism (solid lines). The shapes of the calculated $Q/I$ profiles and their relative line-core amplitudes are in good agreement with the observations reported by Stenflo et al. (2000). Dotted lines: $Q/I$ profiles if the long-lived metastable levels $^2D_{3/2,5/2}$ were completely unpolarized. From Manso Sainz & Trujillo Bueno (2003).

the upper-levels $P_{1/2}$ and $P_{3/2}$ of the $D_1$ and $D_2$ lines, respectively (see Trujillo Bueno et al. 2002b, and Casini et al. 2002). For instance, we now know that the levels of the $D_1$ line are directly sensitive only to radiation intensity, not to the radiation field anisotropy in the $D_1$ line, so that no atomic alignment could be generated in their HFS components if the two levels of $D_1$ were not radiatively connected with other levels in the atom (in particular, with the $P_{3/2}$ upper-level of the $D_2$ line). Thus, the physical origin of the atomic alignment of the HFS components of the ground level of Na I has nothing to do with depopulation pumping.\(^{10}\)

The depopulation pumping process discussed by Trujillo Bueno & Landi Degl'Innocenti (1997) is indeed the key mechanism that polarizes the long-lived lower-levels of the Ca II IR triplet (see Manso Sainz & Trujillo Bueno 2003). However, in the solar atmosphere depopulation pumping does not play any role on the ground-level polarization of sodium. The key mechanism for the $D_1$ line is repopulation pumping. First, note that the $P_{3/2}$ upper-level of the $D_2$ line can be polarized directly via the anisotropy of the solar radiation field, simply because a level with $J = 3/2$ can carry atomic alignment without the need of HFS. The atomic polarization of the level $P_{3/2}$ is transferred to the HFS components of the ground level $S_{1/2}$ via spontaneous emission in the $D_2$ line, and then from the level $S_{1/2}$ to the level $P_{1/2}$ via radiative absorptions in the $D_1$ line. This indicates that the atomic polarization of the lower and upper levels of the $D_1$

\(^{10}\)See Trujillo Bueno (2001) for an introduction to optical pumping mechanisms.
line are intimately inter-related. As a result, in spite of the sizable differences between the lower and upper level lifetimes, the atomic polarization of the lower and upper levels of the $D_1$ line are sensitive to the same magnetic field strengths, independently of the magnetic field inclination (see Fig. 1 of Trujillo Bueno et al. 2002b).

An extra interesting finding has been the following: independently of the magnetic field inclination (e.g., even for a purely vertical magnetic field), the atomic alignment of the HFS components of the ground-level $S_{1/2}$ of Na I and of the upper-level $P_{1/2}$ of the $D_1$ line are practically negligible for magnetic strengths $B > 10$ gauss and virtually zero for $B \geq 100$ gauss. As a result, any contribution to the linear polarization in the core of $D_1$ that arises from atomic alignment is suppressed for magnetic fields sensibly larger than 10 gauss, irrespective of their orientation, so the only expected linear polarization signal for such field strengths would be due to the transverse Zeeman effect.

Fig. 3 shows that the Stokes-$Q$ signature of single scattering events taking place in the presence of a vertical magnetic field changes from antisymmetric for $B \leq 10$ gauss to symmetric for $B \geq 50$ gauss. In particular, note that in the absence of magnetic fields the emergent Stokes-$Q$ profile is antisymmetric and with an amplitude that is 40 times smaller than that corresponding to the $D_2$ line. However, it is very important to point out that this (off-limb) calculation did not include the selective absorption contribution from the atomic polarization of the ground level of sodium ('zero-field' dichroism). Since the emergent fractional linear polarization at the core of a strong spectral line is approximately given by Eq. (3), it is relatively 'easy' to know whether or not the dichroism contribution given by the second term of this equation may be important for magnetic strengths $B < 10$ gauss. Detailed calculations carried out in collaboration with Roberto Casini show that for the $D_2$ line $|\eta_Q/\eta_I| \ll |\epsilon_Q/\epsilon_I|$; i.e., dichroism is totally irrelevant for the $D_2$ line. However, we find that dichroism is indeed expected to play a significant role for the 'enigmatic' $D_1$ line!

An extra and possibly very important physical ingredient that needs to be accounted for both in the density-matrix theory and in the radiative transfer modeling is the influence of bound-free transitions on the $\rho_{Q}^{S}$ values of the Na I levels. Preliminary calculations I have carried out neglecting polarization phenomena suggest that bound-free transitions might be relevant for a correct modeling of both the amplitude and shape of the observed $Q/I$ polarization in the sodium D-lines. Obviously, it will be also very important to investigate the influence of bound-free transitions on the atomic alignment of the upper-level of the Sr I 4607 Å line. We are presently working on these issues.

4. Enhancement of scattering polarization by vertical magnetic fields

In the absence of level crossings between $J$-levels, or between $F$-levels for the case of a HFS multiplet like the Na I $D_2$ line, the theory of the Hanle effect predicts no modification of the emergent linear polarization with increasing strength of a magnetic field oriented parallel to the symmetry axis of the pumping radiation field (e.g., Landi Degl'Innocenti 1985). For this reason, it is commonly believed that the scattering polarization is totally insensitive to vertical magnetic fields.
Figure 3. The emergent linear polarization of the Na I D-lines resulting from 90° scattering events for increasing values of the intensity of a vertical magnetic field. The positive reference direction for Stokes $Q$ is along the line perpendicular to the radial direction through the scattering point. The top panels take into account the feedback of ground level polarization on the atomic polarization of the two upper levels. The two panels with the label “u.l.l.”, instead, neglect the influence of ground-level polarization. The assumed kinetic temperature is 6000 K. Interestingly, the amplitude of the D$_1$ core peaks is particularly sensitive to the Doppler width. From Trujillo Bueno et al. (2002b).
and that in solar limb observations we can only expect to measure the Hanle depolarization caused by inclined magnetic fields.

It is however important to note that this conventional view applies only to ‘simple’ lines like that of Sr I at λ4607 Å, but not to lines that result from transitions between spectral terms whose J-levels (or F-levels for the case of HFS multiplets) cross for a given range of magnetic field strengths. Thus, as shown in Fig. 3, the scattering polarization in the D2 line increases steadily with the magnetic strength, for vertical fields between about 10 and 100 gauss. This is caused by the interferences of the HFS levels in the P3/2 level. In fact, in the 10–50 gauss range, numerous level crossings occur among the magnetic sublevels of the HFS levels with F = 1, 2, and 3 of the P3/2 upper-level of the D2 line. Interestingly, the theoretical prediction that vertical fields in the solar atmosphere produce magnetic enhancement of the scattering polarization in the D2 line (see Trujillo Bueno et al. 2002b), has been observationally confirmed by Stenflo et al. (2002) in a particularly interesting paper on Stokes vector imaging of the sodium doublet with a narrow-band universal filter.

5. The Hanle effect in molecular lines

Molecular scattering polarization has been observed on the solar disk, where the molecular lines are seen in absorption (Stenflo & Keller 1997; Gandorfer 2000; Trujillo Bueno et al. 2001), and just outside the solar limb, where they stand out in emission (Faurobert & Arnaud 2002). Of particular interest is the observational fact, reported by Gandorfer (2000) and Stenflo (2003), that the scattering polarization amplitudes in molecular lines appear to be both spatially invariant and independent of the solar cycle, in sharp contrast to the behavior of many atomic lines. This enigmatic behavior has led Berdyugina, Stenflo & Gandorfer (2002) to conclude that “all the molecular lines with strong scattering polarization are insensitive to magnetic fields” (or “immune to the Hanle effect”) because their effective Landé factors are very small.

It is very important to note that in order for a spectral line to be truly insensitive to the Hanle effect the Landé factors of its lower and upper levels must be zero or so small that

\[ B_H \approx 1.137 \times 10^{-7} / (t_{\text{life}} g_L) \]  

(5)

gives a critical Hanle field much larger than that considered possible for the observed solar region under consideration (t_{\text{life}} and g_L being the level’s lifetime and Landé factor, respectively). However, the upper-level Hanle field of the MgH lines that show scattering polarization peaks in Gandorfer’s (2000) atlas lies between 10 and 100 gauss, approximately (see Fig. 3 of Trujillo Bueno 2003a; see also Landi Degl’Innocenti 2003). For instance, \( B_H \approx 30 \) gauss for the \( Q_1(12.5) \) line at 5171 Å, which is similar to the critical field of atomic lines (e.g., \( B_H \approx 23 \) gauss for the Sr I line at 4607 Å).\(^{11}\) Therefore, the fact that the Landé factors of the molecular levels with high J-values are typically much smaller

\[ \text{The Hanle field resulting from Eq. (5) gives us an estimate of the magnetic strength of a volume-filling turbulent field that would be more than sufficient to produce a sizable change} \]
than those of atomic lines cannot be the resolution of the enigma. Interestingly, as we shall see in the following subsections, such enigmatic behavior is telling us something new about the ‘hidden face’ of solar surface magnetism (see also Trujillo Bueno 2003b).

5.1. The critical Hanle fields of molecular lines

Could it be that the magnetic field strengths needed to produce a significant Hanle effect in molecular lines are much larger than those needed to influence atomic lines? I do not think so because of the following arguments.

In reality, as shown by Eq. (A5) of Trujillo Bueno & Manso Sainz (1999), the formula that one should actually apply for estimating the upper-level Hanle field of a resonance line is

\[ B = \frac{1 + \delta_u (1 - \epsilon)}{1 - \epsilon} B_H, \tag{6} \]

where \( B_H \) (in gauss) is that given by Eq. (5) for \( t_{\text{lif}e} \approx 1/A_{ul} \), \( \delta_u \) is the upper-level depolarizing rate (due to elastic collisions) in units of the Einstein \( A_{ul} \)-coefficient, and \( \epsilon = C_{ul}/(A_{ul} + C_{ul}) \) (being \( C_{ul} \) the inelastic collisional rate between the upper-level ‘u’ and the lower-level ‘l’). Therefore, if one assumes that \( \delta_u \ll 1 \), the \( \epsilon \)-value needed to increase the critical Hanle field by a factor of 10 would be \( \epsilon \approx 0.9 \), while if it were \( \epsilon \approx 0.5 \) then the Hanle field would be \( 2B_H \). It is however unlikely that the \( \epsilon \)-values of molecular lines that result from electronic transitions (such as those of MgH and C\(_2\)) could be much larger than 0.1, because their Einstein \( A_{ul} \)-coefficient is of the order of \( 10^7 \) s\(^{-1}\) for the observed MgH lines and of the order of \( 10^8 \) s\(^{-1}\) for the C\(_2\) lines.\(^{12}\) On the other hand, if we assume that \( \epsilon = 0 \) in Eq. (6) we see that \( \delta_u \approx 1 \) would enhance the critical Hanle field by a factor of 2 only. Obviously, we urgently need detailed investigations to determine the collisional rates of molecular levels. In any case, it is unlikely that \( \delta_u > 1 \), simply because we observe molecular scattering polarization. It is also of interest to note that, according to Omont (1977), “pure depolarization by collisions is rather rare for heavy diatomic molecules”, because “due to the wealth of rotational levels nearby, the probability is higher that a collision induces transitions to another rotational level than between Zeeman sublevels of a given level.”

5.2. An observational test of the molecular Hanle effect

It would be nice to demonstrate observationally the operation of the Hanle effect in molecular line transitions. To this end, it is important to point out that the Landé factors of the upper and lower levels of the \( Q_1 \) lines of MgH have opposite sign to those corresponding to the \( Q_2 \) lines. Therefore, an interesting theoretical prediction is that their Stokes-\( U \) profiles should show opposite signs in high-spatial resolution observations of moderately magnetized regions. An

\(^{12}\)In this respect, it may be helpful to note that at a height of 200 km in the FAL-C semi-empirical model \( \epsilon \approx 5 \times 10^{-3} \) for the 4607 Å Sr \( i \) line, for which \( A_{ul} \approx 2 \times 10^8 \) s\(^{-1}\).
New Diagnostic Windows on the Weak Magnetism of the Sun

Figure 4. The larger the ‘degree of anisotropy’ \( (\mathcal{A} = J_0^\varphi / J_0^\varphi) \) of the pumping radiation field, the greater the \( \sigma_0^\varphi \) values that can be induced, and the larger the emergent \( Q / I \). This figure shows the horizontal variation of the ‘degree of anisotropy’ of the solar continuum radiation at 5000 Å calculated at two heights in a snapshot taken from a realistic hydrodynamical simulation of solar surface convection. The solid lines delineate upflowing regions. Note that in this range of heights where the C\(_2\) lines are ‘formed’ (concerning simulated observations at \( \mu_R = 0.1 \)), there is a strong correlation between the upflowing regions and the degree of anisotropy of the continuum radiation.

Observational verification of this effect on the Stokes-\( U \) profiles of molecular line pairs, like the \( Q_1(12.5) \) and \( Q_2(11.5) \) of MgH, would provide an irrefutable proof of the operation of the Hanle effect on solar molecular lines. A similar experiment can be devised for suitably chosen line pairs of other molecules. Note that this observational test requires of high spatial and temporal resolution, because \( U = 0 \) if the azimuth of the magnetic field vector turns out to have a random variation within the resolution element of the observation.

5.3. A possible resolution of the enigma

The resolution of the enigma of why the molecular scattering polarization amplitudes appear to be invariant requires first answering the following question: Which photospheric regions contribute to the observed molecular scattering polarization? The answer is that the observed scattering polarization in molecular lines comes mainly from the upflowing regions of the solar photosphere (i.e., precisely from the regions where the weakest magnetic fields tend to be located). This important conclusion is partly demonstrated in Fig. 4, which shows that the weakly magnetized upflowing regions are precisely the locations where the anisotropy factor of the solar continuum radiation is the largest. In addition, chemical equilibrium calculations show that at heights in the solar atmosphere where the observed molecular scattering polarization is originated (i.e., between approximately 150 and 250 kilometers for the C\(_2\) lines observed at \( \mu_R = 0.1 \)) there is also a very significant correlation with the horizontal fluctuation of the molecular number density.
Therefore, the resolution of the enigma is that the observed scattering polarization in molecular lines is coming mainly from the upflowing regions of the solar photosphere, where the weakest magnetic fields tend to be located. The scattering polarization in molecular lines is sensitive to the Hanle effect. What happens is that the probability density function (PDF) that describes the distribution of magnetic fields in the (granular) upflowing regions of the solar photosphere is relatively narrow and centered at $B = 0$ gauss, so that the magnetic fields that could in principle produce a significant Hanle depolarization have a very small filling factor.

5.4. Diagnostics of ‘granular’ magnetic fields via the Hanle effect in $C_2$ lines

How narrow is the PDF of the granular upflowing regions of the ‘quiet’ solar photosphere? Fig. 5 in Trujillo Bueno (2003b) gives an estimate of the ‘upper-level Hanle fields’ for the lines of the P and R branches of $C_2$ molecules, which show beautiful scattering polarization signatures on the Sun (see the atlas of Gandorfer 2000). Interestingly, because the Landé factors of the upper-levels of the $R_2$ ($P_2$) lines are much smaller than those of the $R_1$ ($P_1$) and $R_3$ ($P_3$) lines, the magnetic field strength needed for a significant Hanle-effect suppression of the scattering polarization signal is considerably smaller for the $R_1$ ($P_1$) and $R_3$ ($P_3$) lines than for the $R_2$ ($P_2$) lines. For example, for $C_2$ lines of the R branch with total angular momentum $30 < J < 40$ the critical Hanle field lies between only 8 and 16 gauss for the $R_1$ and $R_3$ lines, but between 200 and 400 gauss for the $R_2$ lines. This very sizable difference in the sensitivity to the upper-level Hanle effect between the $R_2$ ($P_2$) lines and the $R_3$ ($P_3$) lines is being used by us for constraining the weak-field part of the solar ‘magnetoturbulent spectrum’ in relatively deep regions of the solar photosphere. The interesting point here is that the critical fields required to modify the atomic polarization of the upper-levels of the $R_2$ ($P_2$) lines are so large that no Hanle depolarization is expected for them in quiet (inter-network) regions of the solar photosphere. The theoretical interpretation of simultaneous spectropolarimetric observations of such $R_2$ ($P_2$) reference lines and of $R_3$ ($P_3$) lines (which are sensitive to magnetic strengths similar to those that cause Hanle depolarization in atomic lines), offers a new spectral window to explore the distribution of magnetic fields in the upflowing regions of the solar photosphere.

As it can be seen in Gandorfer’s (2000) atlas, the ratio ($\mathcal{R}$) of the observed fractional polarizations between $R_2$ ($P_2$) lines and $R_3$ ($P_3$) lines is $\mathcal{R} \approx 2$, concerning those $R_2$ ($P_2$) lines which are perfectly blended with $R_1$ ($P_1$) lines. However, a detailed investigation of the scattering polarization in such molecular lines taking into account the overlapping effect between the $R_1$ ($P_1$) and $R_2$ ($P_2$) lines shows that there is no significant magnetic depolarization of the $R_3$ ($P_3$) lines with respect to the $R_2$ ($P_2$) lines. Actually, if there were a significant magnetic depolarization the above-mentioned ratio $\mathcal{R}$ would be larger than 2, which is not observed. Therefore, only a relatively small fraction of the volume occupied by the photospheric regions that are effective in producing the observed molecular polarization can be filled with magnetic fields of strength similar or larger than the critical Hanle fields of the $R_1$ ($P_1$) and $R_3$ ($P_3$) lines. In fact, as we shall show in a forthcoming publication, our empirically-determined PDF
turns out to be very narrow, implying that most of the upflowing photospheric volume is occupied by very weak fields.

5.5. On-disk versus off-limb observations and the role of ground-level polarization on the molecular scattering polarization

As shown by Eq. (2), the linear polarization observed on-disk may have a contribution from the atomic polarization of the upper-level, but also an extra one from dichroism if the lower-level is significantly polarized. This Eq. (2) can be reformulated (without making any assumption on whether the line is weak or strong) to yield\(^\text{13}\)

\[
\left( \frac{Q}{I} \right)_{\text{on-disk}} \approx \frac{3}{2\sqrt{2}} \frac{\eta_T^l}{\eta_T^l + \eta_T^c} \left( 1 - \mu^2 \right) \left[ \frac{S_l}{S_\nu} \mathcal{W} \sigma_0^2(\text{up}) - \mathcal{Z} \sigma_0^2(\text{low}) \right],
\]

where \(S_l\) is the line source function and \(S_\nu\) the total source function, respectively.\(^\text{14}\) Note that \(S_\nu \approx B_\nu\) for weak molecular lines (being \(B_\nu\) the Planck function), while \(S_l \approx (1 - \epsilon)J + \epsilon B_\nu\) (being \(\epsilon\) the probability that an excitation event is caused by inelastic collisions, and \(J\) the mean intensity of the solar radiation at the line frequency). Therefore, in Eq. (7) \(S_l/S_\nu \approx S_l/B_\nu\) for weak lines, and the maximum values of \(S_l/B_\nu\) are obtained when assuming that \(S_l \approx J\). Interestingly, in the upflowing regions of Asplund’s et al. (2000) three-dimensional hydrodynamical model of the quiet solar photosphere \(1 < J/B_\nu < 2\) for \(\lambda = 5200\ \text{Å}\) at heights \(h\) between 100 and 300 km, being the most common value \(J/B_\nu \approx 1.3\) at \(h = 200\ \text{km}\).

On the other hand, dichroism plays no role on the linear polarization observed off-limb since we may assume that the emitting layer is optically thin. Therefore, we need to retain only the first term of Eq. (2), which can be simplified because \(\epsilon_T^l \ll \epsilon_T^c\) when observing off-limb. As a result,

\[
\left( \frac{Q}{I} \right)_{\text{off-limb}} \approx \frac{3}{2\sqrt{2}} \mathcal{W} \sigma_0^2(\text{up}).
\]

It is very important to point out that the presence of ground-level polarization may have a significant feedback on the fractional polarization of the upper-level. However, the polarizability factor \(W_2\) of given scattering transitions that Faurobert & Arnaud (2002) tried to determine empirically from their off-limb observations is a concept based on the assumptions of completely unpolarized lower-level and that the scattering events are taking place in the absence of any upper-level depolarizing mechanism (e.g., Stenflo 1994). It is not difficult to show that, in the general case,

\[
W_2 = \frac{4Q/I}{\sqrt{2A(3 + Q/I)}},
\]

\text{13}See also the alternative expression given by Landi Degl’Innocenti (2003) for weak lines.

\text{14}Note that, from now on, I use the symbol \((\frac{Q}{I})_{\text{on-disk}}\) to indicate the \((\frac{Q}{I})_{\text{line}}\) observed on-disk, and \((\frac{Q}{I})_{\text{off-limb}}\) for the \((\frac{Q}{I})_{\text{line}}\) observed off-limb.
where $A = J^2_0 / J^0_0$ quantifies the ‘degree of anisotropy’ of the photospheric radiation field, being $J^0_0$ the radiation field tensors introduced by Landi Degl’Innocenti (1984). Therefore, in principle, one should not be surprised to find discrepancies between empirical and theoretical $W_2$-factors, simply because the $Q/I$ observed off-limb may be affected by the presence of ground-level polarization (i.e., because the actual value of $\sigma_0^2(u)$ depends on $\sigma_0^2(\ell)$). On the other hand, since the ‘empirical $W_2$ values’ were determined by Faurobert & Arnaud (2002), from an equation equivalent to our Eq. (9), by using the calculated anisotropy factor $A$ in a plane-parallel semi-empirical solar atmospheric model, it is clear that any underestimation of $A$ would imply an artificial overestimation of $W_2$.\footnote{For off-limb observations at a given height above the visible limb one should actually calculate the anisotropy factor in spherical geometry, which gives significantly larger $A$-values than those obtained via the plane-parallel approximation. When this is taken into account, one then finds empirical $W_2$-values for the C$_2$ lines that are significantly \textit{smaller} than those given by Faurobert & Arnaud (2002), which were found to lie between 0.13 and 0.26. However, the correctly derived values are still \textit{larger} than the theoretical $W_2 \approx 0.1$ value.}

Figure 5 shows an example of multilevel model calculations of the scattering polarization in the $P_3(35)$ line of C$_2$ at 5149.198 Å including its sensitivity to a microturbulent and isotropically distributed magnetic field (see Asensio Ramos & Trujillo Bueno 2003, for details on the chosen multilevel molecular model). The fractional linear polarizations has been calculated using Eq. (8) (dashed lines: the off-limb case) and Eq. (7) with $S_I/S_\nu = 1$ (solid lines: the on-disk case). These $Q/I$ values have been used in Eq. (9) to obtain the corresponding polarizability factor as a function of the magnetic field strength.

The three left panels correspond to the case in which the lower-level is assumed to be completely depolarized by elastic collisions. In this case, $(Q/I)_{\text{on-disk}}$ is also fully due to the emission events from the polarized upper-level. The upper-level fractional alignment, $\sigma_0^2(u)$, remains practically constant for magnetic strengths $B < 10$ gauss. For stronger fields, the upper-level Hanle effect reduces the $\sigma_0^2(u)$ values up to the point in which the Hanle saturation limit is reached. Note that for fields weaker than 10 gauss, the numerically calculated polarizability factor $W_2$ is similar to the theoretical value, whose limit for $J \rightarrow \infty$ is $W_2 = 0.1$.

The three right panels show what happens when we allow for the possibility of lower-level polarization, including the dichroism contribution to $(Q/I)_{\text{on-disk}}$. Interestingly, the values obtained for this quantity assuming $S_I/S_\nu = 1$ are similar to those corresponding to the completely unpolarized lower-level case shown in the left panels, which indicates that if $S_I/S_\nu \approx 1$ it is impossible to obtain any observational hint on the presence of ground-level polarization by means of on-disk observations (see Landi Degl’Innocenti 2003, for the analytical proof of this conclusion). Note, however, that this does not apply to $(Q/I)_{\text{off-limb}}$. As shown in the figure, for C$_2$ lines the value of $(Q/I)_{\text{off-limb}}$ increases significantly for $B < 10$ milligauss, being $(Q/I)_{\text{off-limb}} \approx 1.5\%$ for $B = 0$ gauss. Interestingly, if this fractional polarization amplitude is introduced in Eq. (9) we obtain a polarizability factor $W_2 \approx 0.14$, which is significantly larger than the theoretical one. This provides a possible explanation of the (surprisingly large) empirical $W_2$-values that result from Faurobert & Arnaud (2002) observations.
Figure 5. Numerical simulation of the Hanle effect produced by a volume-filling turbulent field in the $P_3(35)$ line of $C_2$ at 5149.198 Å. The three left panels assume that the lower-level is unpolarized, while the three right panels account for the possibility of lower-level polarization. The top panels show the fractional atomic alignment of the upper-level (solid lines) and of the lower-level (dashed lines). The middle panels give the emergent fractional polarization for the limiting case of a on-disk observation at $\mu = \mu_R = 0$ (solid lines) and for an off-limb observation (see the dashed lines, and note that they cannot be distinguished from the solid line in the left panel). It is important to point out that while the amplitude of the off-limb simulation can be compared directly with real observations, that of the on-disk calculation would have to be multiplied first by a scaling factor smaller than unity because the on-disk polarization results from a radiative transfer process. The bottom panels give the polarizability factor that results when the $Q/I$ values of the middle panels are used in Eq. (9). The dotted lines indicate the theoretical $W_2$-value according to the formulae given by Landi Degl’Innocenti (2003).
Figure 6. Inclination ($\theta_B$), azimuth ($\chi_B$), and strength of the magnetic field vector inferred from the observed He I 10830 polarization in spicules at a given spatial point. The bottom panel illustrates that the light selected by the spectrograph slit stems from chromospheric spicular material.

Similar numerical calculations for the $Q$-lines of MgH indicate that $W_2 \approx 0.4$ if the lower level is unpolarized and the magnetic strength is significantly below the corresponding upper-level critical field. Interestingly, in the Hanle regime in which the lower-level is saturated but the upper-level is not, we find polarizability factors that are slightly (but significantly) smaller than 0.4.

6. The magnetic field of solar chromospheric spicules

Let us finally address the following question of how we could investigate the magnetism of the upper solar chromosphere. In my opinion, one attractive possibility is via spectropolarimetric observations of solar spicules. All theoretical models aimed at explaining the origin of spicules invoke magnetic field effects (see the review by Beckers 1972). What has really been lacking up to now are spectropolarimetric investigations to infer the strength and geometry of the magnetic field that is thought to channel the spicule motion. To fill this gap, we have carried out an investigation which combines observational and theoretical spectropolarimetry.
Figure 6 shows an example of the full Stokes vector of the He I 10830 Å multiplet, which we have observed with the Tenerife Infrared Polarimeter (TIP) attached to the Vacuum Tower Telescope (VTT). The spectrograph slit was located ~2 arcsec off the East solar limb and parallel to it, thus crossing spicular material as illustrated in the lower part of the figure. This spectropolarimetric observation is very encouraging, especially because of the detection of a non-zero Stokes-U profile. According to the theory of the Hanle effect, this Stokes-U profile is the observational signature of the presence of a weak magnetic field inclined with respect to the solar radius vector through the observed point. Note that the Stokes-V signal is at the noise level, indicating that either the field is very weak (the most reasonable possibility) and/or that the field is perpendicular to the line of sight. A best fit to the observations can be achieved, at various levels of sophistication, via theoretical modeling of the Hanle and Zeeman effects. For example, if we assume that the scattering polarization is produced by an optically thin plasma we obtain the solid lines of Fig. 6. Our theoretical modeling of the observed Stokes Q, U and V profiles is notable. The discrepancy found in Stokes-I around the wavelength location of the blue component of the He I 10830 Å multiplet indicates that the optically thin assumption is not suitable for Stokes-I. A more detailed theoretical modeling including radiative transfer effects along a line of sight going through many individual spicules yields excellent agreement with the observations and indicates the importance of developing the research field of radiative transfer in stochastic media.

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Discussion

NAGENDRA: Do I understand correctly that the term ‘dichroism’ that you use is similar to the absorption coefficient of a medium being different for ordinary and extra-ordinary waves?
J. TRUJILLO BUENO: Yes! However, note that the interesting point here is that we have “zero-field” dichroism in the quiet solar atmosphere, simply because the lower-levels of many spectral lines are significantly polarized.

N. FEAUTRIER: Could you comment on the role of elastic collisions on the sodium D$_1$ line?
J. TRUJILLO BUENO: I think that the line-core radiation of the D$_1$ line comes mainly from relatively cool regions of the upper solar photosphere, where the total hydrogen number density is not sensibly larger than 10$^{14}$ cm$^{-3}$.  

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