DIAGNOSTICS WITH THE HANLE EFFECT

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Abstract. The Hanle effect has been extensively used for the determination of the magnetic field strength and direction in solar prominences. Here we address the problem of the diagnostics of weak magnetic fields in the solar photosphere and chromosphere by means of their Hanle effect in some selected absorption lines. As this is a relatively new area we will focus on the diagnostic methods and summarize some results that relate to the presence of a weak, turbulent magnetic field in the photosphere and to the chromospheric magnetic canopy. Finally we will outline some directions for future work.

Key words: Polarization – Magnetic fields – Solar spectrum

1. Introduction

Stenflo et al. (1983a, b) have made an extensive survey of linear polarization in solar lines covering the wavelength range 3165–9950 Å. These observations carried out near the solar limb and outside active regions show evidence of a wide variety of resonant and fluorescent scattering effects. Even more features are discovered when the polarization sensitivity is increased (see Stenflo, these proceedings). The diagnostic contents of this polarization spectrum is still far from being fully investigated.

The observed resonance polarization is due to the coherent scattering of the anisotropic photospheric radiation field by the atoms. In the presence of a weak magnetic field, when the Zeeman splitting is on the order of the natural line width, the resonance polarization is reduced, and the polarization plane is rotated. This is the so-called Hanle effect, which is due to the relaxation of the coherences between the Zeeman sublevels. In the presence of a weak magnetic field with mixed polarities over the resolution element of the telescope there is no prefered direction for the rotation of the polarization plane, but the depolarization is not cancelled out. This provides a diagnostic tool for weak magnetic fields with mixed polarities on small scales, which do not give rise to detectable Zeeman polarization. This was first pointed out by Stenflo (1982) who suggested that such weak magnetic fields, although hidden from magnetograms, could carry a significant part of the solar magnetic flux.

The indirect diagnostic of these fields, based on the Hanle effect, requires detailed non-LTE radiative transfer calculations including polarization. Until now this has been done essentially for two resonance lines, namely the Ca I 4227 Å and the Sr I 4607 Å lines (Faurobert-Scholl, 1992, 1993, 1994;

Faurobert-Scholl et al., 1995). Both are normal triplets which show relatively high linear polarization rates outside active regions, typically on the order of a few percent at 10 arcsec inside the solar limb. We have used center-to-limb observations performed by Stenflo et al. (1980) with the Stokes I spectro-polarimeter at Sac Peak. New observations have been made recently by Keller and Stenflo with ZIMPOL, and by Arnaud and Penn with ASP.

The sensitivity of a line to the Hanle effect is in that part of the magnetic field strength domain, where the shift of the Zeeman sub-levels is on the order of the natural line width (Bommier, these proceedings). This gives

$$B \approx \Gamma_R/0.88g_J,$$

where $B$ is in G and $\Gamma_R$ in units of $10^7$ s$^{-1}$, while $g_J$ is the Landé factor of the upper level. For the Sr I and Ca I lines $g_J = 1$ and $\Gamma_R = 2.01 \times 10^8$ s$^{-1}$ and $2.18 \times 10^8$ s$^{-1}$, respectively. These lines are sensitive to the Hanle effect for magnetic fields of about 20 G, the useful range being approximately 5–100 G.

2. Diagnostic method

The first step of the diagnostic method is to compute as accurately as possible the resonance polarization which would be observed in the absence of a magnetic field. Resonance polarization is very sensitive to the non-LTE processes which contribute to the line formation, such as frequency redistribution, depolarizing collisions, velocity fields and multiple scattering. It is obviously highly sensitive to the anisotropy of the line radiation field, which depends on the atmospheric structure. The results are then compared with the observed polarization, and the discrepancy is interpreted in terms of the Hanle effect. Let us note that the Hanle effect does not affect the polarization in the line wings (Frisch, these proceedings) and does not change the intensity profiles, since very weak magnetic fields do not significantly modify the line absorption profile. This allows us to constrain, at least partly, the first step of the calculations by requiring that the center-to-limb variations of the line intensity profile should be well reproduced. This is a necessary requirement, but it does not completely ensure that we are computing the line polarization correctly. This will be discussed further in the following.

2.1. Multi-level transfer of polarized radiation

As we are dealing with low polarization rates (a few % at most), we assume that the polarization in the lines does not affect the populations of the atomic levels. We first solve a “standard” non-LTE multi-level transfer problem without polarization and then compute the resonance line polarization.
using an equivalent two-level atom formalism for the line source function. The non-polarized calculation provides the optical thickness in the line of interest, together with the pseudo creation and destruction terms, due to level coupling, which appear in the equivalent two-level form of the source function. This procedure assumes that level coupling does not affect the polarization of the line. This would not apply to the computation of Ca II H and K resonance polarization because, interference takes place between the $J = \frac{1}{2}$ and $\frac{3}{2}$ upper levels (Stenflo, 1980). It is however a reasonable assumption for the Ca I and Sr I lines.

The Ca I and Sr I model atoms have been represented by two bound levels and a continuum. As both lines have large oscillator strengths, level coupling with other atomic levels has been neglected. The non-polarized transfer equation, coupled with the statistical equilibrium equations for the atomic levels, has been solved with an iterative method based on the equivalent two-level atom approach. Partial frequency redistribution in the line has been accounted for in these calculations.

2.2. Calculations of resonance polarization

Let us first say a few words about the numerical method that is used to compute the line polarization.

2.2.1. Numerical method

We have to solve the following vector transfer equation

$$\mu \frac{\partial I(\tau, x, \Omega)}{\partial \tau} = (\beta + \phi(x))(I(\tau, x, \Omega) - S(\tau, x, \Omega)).$$

(2)

Standard notations are used. $\mu = \cos \theta$, where $\theta$ is the heliocentric angle, $\tau$ is the line average optical depth and $x$ is the frequency. $I$ is the Stokes vector. The vector source function $S$ is related to the line source function $S_L$ by

$$S(\tau, x, \Omega) = \frac{\phi(x)S_L + \beta BU}{\phi(x) + \beta},$$

(3)

where $B$ is the Planck function and $U$ is the unpolarized unit vector. We stress that, as we are dealing with a realistic solar model, the Voigt absorption profile $\phi(x)$ and the ratio of the continuum opacity to line integrated opacity, $\beta$, are both depth-dependent. The line source function $S_L$ is written

$$S_L(\tau, x, \Omega) = \{sc(\tau, x, \Omega) + (\varepsilon' B + \eta B^*)U\}/(1 + \varepsilon' + \eta),$$

(4)

where $sc$ denotes the scattering term. This is the generalization to the vectorial case of the equivalent two-level atom formulation given by Mihalas
(1978, pp. 359, 360), for a two-level atom with continuum. The extra creation term $\eta B^*$ and sink term $\eta$ are due to the coupling with the continuum. The scattering term is discussed in detail in Frisch’s paper (these proceedings).

In the absence of a magnetic field the radiation field is axially symmetric, and we can apply the Feautrier method to the vector transfer equation in order to compute both the intensity and the polarization profiles (Faurobert, 1987). This also holds in the presence of a weak, isotropic turbulent magnetic field that we will consider in the following. The phase matrix is only modified in the line core by magnetic fields.

In the presence of an anisotropic magnetic field, the radiation field is no more axially symmetric. An iterative procedure, based on the azimuthal Fourier expansion of the radiation field, can be used to compute the line polarization in the presence of the Hanle effect (Faurobert-Scholl, 1991).

Let us now examine the effect of various physical mechanisms on the resonance polarization in the Ca I and Sr I lines. As part of this study we need to find out whether it is possible to constrain these mechanisms by fitting the intensity profiles, which are independent of the Hanle effect. When this is not possible we have to be confident enough about the way that we model these mechanisms, because they affect the diagnostics of the weak magnetic fields.

2.2.2. Partial frequency redistribution

Partial frequency redistribution affects more strongly the polarization profiles than the intensity profiles. This is illustrated for the Ca I line in Fig. 5 of Frisch’s paper (these proceedings). A correct form for the redistribution function must be used, as discussed in Frisch’s paper. Let us just recall here that angle-averaged forms of the redistribution function may be safely used, even for strong resonance lines.

In contrast to the Ca I line, the Sr I line core polarization is almost insensitive to partial frequency redistribution effects. The reason is that, because of the very low abundance of strontium in the solar atmosphere, the Sr I line is not a strong line.

2.2.3. Elastic collisions

Elastic collisions may have much stronger effects on the polarization profiles than on the intensity profiles. This is illustrated, in the case of the Sr I line in Fig. 1, which shows the intensity and polarization profiles computed with two different values for the elastic collision cross-section. The Sr I line is formed in the solar photosphere, in regions where the density is large, and where the rate of depolarizing collisions, denoted by $D^{(2)}$, may take values on the order of or larger than the radiative deexcitation rate. Depolarizing collisions have the same effect as the Hanle effect due to a weak, mixed polarity
magnetic field. The diagnostics of these fields by means of the Hanle effect thus requires a very good knowledge of the depolarizing collision rate. This is the reason why precise quantum mechanical calculations of this quantity have been performed recently, using an accurate form for the inter-atomic potential (Faurobert-Scholl et al., 1995). The situation is very different in the case of the Ca I line, because the line core is formed in the low chromosphere, in regions where the density is low. The line core polarization is thus not affected by elastic collisions.

Let us briefly recall the results on the elastic collision cross-sections. For electron temperatures between 4000 and 10,000 K the broadening due to elastic collisions, denoted by $\Gamma_C$, and the depolarizing collision rates may be represented by the following analytical expressions: For the Sr I line

$$\Gamma_C = \gamma_w N_H (T/5000)^{0.16}, \quad \text{with } \gamma_w = 2.73 \times 10^{-8}, \quad D^{(2)} \simeq 0.5 \Gamma_C.$$  \hspace{1cm} (5)

For the Ca I line

$$\Gamma_C = \gamma_w N_H (T/5000)^{0.20}, \quad \text{with } \gamma_w = 2.90 \times 10^{-8}, \quad D^{(2)} \simeq 0.6 \Gamma_C.$$  \hspace{1cm} (6)

$N_H$ denotes the number density of neutral hydrogen. We notice that these results are quite different from the Van der Waals approximation, the numerical coefficients $\gamma_w$ being twice as large and the temperature dependence lower.

2.2.4. Velocity fields

Microturbulent and macroturbulent motions also affect the intensity and the polarization profiles. The microturbulent velocity is usually taken from the solar model. The effect of the macroturbulent velocity field has been represented by a smearing of both the intensity and the polarization profiles. We have determined the macroturbulence by fitting the observed center-to-limb variations of the line width and central intensity. The line width of Sr I is dominated by macroturbulence, so our procedure puts strong constraints on this quantity. However, the width of the polarization peak in the line core is generally smaller than the width of the intensity profile, and this observed property is not accounted for in the present calculations. A more refined treatment of turbulence may be necessary to recover this property. We will discuss this point further below.

The sensitivity of both the intensity and polarization to a change in the microturbulent velocity is illustrated in Fig. 2, which shows the profiles without and with smearing due to macroturbulence, at $\mu = 0.09$, for two different models of microturbulence. One is taken from the VAL3C solar model, while the other corresponds to a depth-independent microturbulence of 1 km/s (MIC1 model). The two models differ mainly in the upper photosphere, where the VAL3C microturbulence decreases to values on the order of 0.5 km/s.
Fig. 1. Intensity and polarization profiles of the Sr I 4607 Å line at $\mu = 0.09$, for two different values of $\gamma_\nu$ (Eq. (5)). Full lines $\gamma_\nu = 2.8 \times 10^{-8}$, dashed lines: $\gamma_\nu = 1.4 \times 10^{-8}$. Thin lines: profiles obtained without macroturbulence, thick lines: profiles smeared by macroturbulent motions.

The smeared intensity profile is not very sensitive to the microturbulent model, in contrast to the line core polarization. We find that the resonance polarization in the Sr I line obtained after smearing is somewhat larger for the MIC1 model. The comparison with the observed rates then leads to somewhat stronger turbulent magnetic fields than with the VAL3C model (cf. Fig. 3).

For the Ca I line the procedure we have just described could not be applied, because the line width is not controlled by macroturbulence. The macroturbulence was determined from the intensity at line center only. As the line center intensity observed by Stenflo et al. (1980) increases strongly towards the solar limb, we have been led to consider a very anisotropic macroturbulence with a vertical component of 1.5 km/s and a horizontal component of 3.5 km/s. This allows us to recover the line center intensity observed up to $\mu = 0.2$. We note that the value of the vertical component is in agreement with a previous estimate by Lites (1974). The horizontal component had, as far as we know, not been determined before. This strong apparent anisotropy might also reflect a height increase of the macroturbu-
Fig. 2. Intensity and polarization profiles at $\mu = 0.09$ of the Sr I 4607 Å line. Full lines: VAL3C microturbulent velocity. Dashed lines: Depth-independent microturbulence of 1 km/s. Thin lines: No macroturbulence. Thick lines: With macroturbulent smearing.

ence, because the intensity observed near the solar limb is formed higher in the chromosphere.

Let us stress that the effect of an anisotropic or depth-dependent macroturbulent velocity fields on resonance polarization could be quite different from a simple smearing of the polarization peak. Theoretical investigations of this issue should be done in the near future, because this has strong consequences for the diagnostic methods based on the Hanle effect. Some work has recently been done by Briquet and Sahal-Bréchot, in the case of the CaI line (private communication). The polarization formation is treated with the last scattering approximation using the observed center-to-limb variations of the line intensity. A moving atom scatters the incident line radiation field, which is identified with the observed line intensity, and the polarization of the re-emitted radiation is calculated for the resonant frequency, assuming that the atom absorbs and reemits radiation at this frequency only. Then an average over the anisotropic maxwellian velocity distribution of the atoms is performed. This procedure assumes that the polarization is formed higher in the atmosphere than the intensity profile, and does not take into account any frequency coupling due to scattering. In the absence of macroturbulent velocities, the resonance polarization at line center is overestimated by a
factor of two as compared with a full polarized transfer calculation. It may be used to get a first qualitative estimate of the effect of an anisotropic macroturbulent velocity. The results are the following. When the anisotropy is along the vertical direction, the line core polarization is increased with respect to the case where there is no macroturbulent motions. In contrast, if the anisotropy is horizontal the line polarization decreases. The reason is that the limb-darkening of the line radiation field "seen" in the rest frame of a moving atom is larger (respectively smaller) if its velocity is perpendicular (respectively parallel) to the solar surface. In the first case, the Doppler shift increases the incident intensity seen at $\mu = 1$ for the resonant frequency of the atom, in the second case it increases the incident intensity seen at $\mu = 0$. Multiple scattering has to be treated in detail to get quantitative estimates of these effects.

2.2.5. Inhomogeneities in the solar atmosphere
The effect of modifications of the solar model on the polarization profiles has not been systematically studied. We believe that the "average" atmospheric structure is now quite well known in quiet regions of the sun. We have used the model C of Fontenla et al. (1993), which is an improved version of the VAL3C model (Vernazza et al., 1981). This average semi-empirical model was established from intensity observations in continua and in some spectral lines. However, as the presence of inhomogeneities in the solar atmosphere may affect the intensity profiles and the polarization profiles very differently, the average solar model may not be well adapted to represent polarization data. One way of checking this point would be to compute the spatial average of intensity and polarization profiles obtained from 2D atmospheric models representing some inhomogeneities in the solar atmosphere. For the Sr I line, a two-component model of the photosphere, modeling the solar granulation, could be used. This idea will be investigated in the future. It requires 2D radiative transfer calculations with polarization. Numerical codes designed for such 2D calculations are now under development.

2.3. Hanle effect

The Hanle effect due to a weak, mixed polarity magnetic field is computed under the assumption that the correlation length of the field is smaller than a typical photon mean free path. In this case its effect may be calculated in the micro-turbulent limit. We then only need to replace in the transfer equation the Hanle phase matrix by its average over the distribution of magnetic field strengths and directions.

An isotropic distribution of field vectors is used to model the turbulent magnetic field in the solar photosphere. This is in agreement with previous estimates by Stenflo (1989). For the chromospheric canopy we consider hori-
Diagnostics with the Hanle Effect

In the first case the average Hanle phase matrix is

\[ \langle P_H(\mu, \mu', B) \rangle = P_{is} + \frac{3}{4} \left[ 1 - 0.4 (S_I^2 + S_{II}^2) \right] W_2 P_0^{(2)}(\mu, \mu'). \]  

(7)

The magnetic field strength enters only in the expressions for \( S_I \) and \( S_{II} \):

\[ S_I = \frac{\gamma_H}{\sqrt{1 + \gamma_H^2}}, \quad S_{II} = \frac{2\gamma_H}{\sqrt{1 + 4\gamma_H^2}}, \]  

(8)

with

\[ \gamma_H = 0.88 gJ \frac{B}{\Gamma_R + D^{(2)}}. \]  

(9)

Here \( B \) denotes the field strength, measured in G, while \( gJ \) is the Landé factor of the upper level. The coefficients \( \Gamma_R \) and \( D^{(2)} \) are given in units of \( 10^7 \) s\(^{-1}\).

We recall that \( W_2 \) is a constant that depends on the quantum numbers \( J \) and \( J' \) of the lower and upper levels of the transition. For a normal triplet \( W_2 = 1 \). The matrix \( P_{is} \) is the isotropic phase matrix (first position unity, remaining positions zero), while

\[ P_0^{(2)}(\mu, \mu') = \frac{1}{2} \begin{pmatrix} \frac{3}{2}(1 - 3\mu^2)(1 - 3\mu'^2) & (1 - 3\mu^2)(1 - \mu'^2) \\ (1 - \mu^2)(1 - 3\mu'^2) & 3(1 - \mu^2)(1 - \mu'^2) \end{pmatrix} \]  

(10)

When the magnetic field strength is stochastic and described by a distribution function \( f(B) \), the average values of \( S_I^2 \) and \( S_{II}^2 \) depend not only on the mean value, but also on the higher moments of the field strength distribution. For the sake of simplicity, we assume that the distribution function is a Dirac delta function. The value of the field strength that we will determine may be considered as the “effective” magnetic field strength.

In the case of a horizontal magnetic field with random azimuths,

\[ \langle P_H(\mu, \mu', B) \rangle = P_{is} + \frac{3}{4} \left( 1 - 0.75 S_{II}^2 \right) W_2 P_0^{(2)}(\mu, \mu'). \]  

(11)

The determination of the weak magnetic fields is made by comparison of the calculated depolarization at line center, denoted by \( Q/Q_0 \), with the same quantity derived from the observed polarization, \( Q_{obs}/Q_0 \). This is illustrated in Figs. 3a, b in the case of the Sr I line. The results have been obtained with a microturbulent velocity of 1 km/s, as well as with the VAL3C microturbulence. We notice that for this spectral line the Hanle depolarization \( Q/Q_0 \) is almost insensitive to the adopted microturbulence, and only weakly sensitive to the smearing due to macroturbulence. In constrast, the ratio \( Q_{obs}/Q_0 \) is very sensitive to both quantities because of the sensitivity.
Fig. 3. Hanle depolarization in the Sr I line core, due to depth-independent turbulent magnetic fields. Thin symbols show results obtained without macroturbulence, while for the thick symbols macroturbulent smearing has been applied. The thick bars give $Q_{\text{obs}}/Q_0$. Fig. 3a: microturbulent velocity of 1 km/s. Fig. 3b: VAL3C microturbulent velocity.

of the non-magnetic resonance polarization $Q_0$. As a consequence the determination of the strength of the turbulent magnetic field also depends on both quantities.

3. First results

3.1. TURBULENT MAGNETIC FIELD IN THE SOLAR PHOTOSPHERE

The polarization observed in the Sr I line core is significantly smaller than the resonance polarization calculated in the absence of a magnetic field. It is consistent with the presence of a turbulent magnetic field with an effective
strength between 10 and 20 G in the region between 200 and 400 km above \( \tau_{5000} = 1 \) (Faurobert-Scholl et al., 1995).

This result is in good agreement with theoretical calculations of the passive transport of the turbulent magnetic field by turbulent motions in the solar photosphere (Petrovay, 1994, Faurobert-Scholl et al., 1995). According to these calculations the turbulent magnetic field decreases smoothly from values on the order of 30–50 G at \( \tau_{5000} = 1 \) to less than 10 G at 500 km above \( \tau_{5000} = 1 \).

3.2. Chromospheric magnetic canopy

The observations of the linear polarization in the Ca I line core may be used to investigate weak magnetic fields in the low chromosphere where the line core is formed. The comparison of the observed polarization rates with the calculated resonance polarization gives a surprising result. Observations performed near the solar limb (\( \mu \leq 0.3 \)) are in agreement with non-magnetic calculations, whereas closer to disk center the observed polarization is significantly larger. Let us note that this comparison has been made for calculated profiles which were smeared to represent the effect of macroturbulent velocity fields.

In Faurobert-Scholl (1994) it is shown that the Hanle effect due to a magnetic canopy lying below the height where the line core is formed actually causes an increase of the Ca I line core polarization observed at \( \mu \geq 0.3 \). This surprising effect is a consequence of multiple scattering in the solar chromosphere. The line core polarization goes through a positive maximum between \( z = 700 \) and 900 km and becomes negative (parallel to the solar limb) at higher altitudes, where it does not change anymore. The Hanle effect of a weak magnetic field located in the region of the positive maximum locally decreases the positive contribution, so that the emergent negative polarization gets enhanced as compared with the non-magnetic situation. Let us note that a positive polarization maximum in the region where the line optical depth is between 1 and 10 is also present for lines formed in isothermal atmospheres. This is a property of multiple Rayleigh scattering.

4. Conclusions

Diagnostic methods based on the Hanle effect are at a beginning stage. They require, as a first step, reliable calculations of the resonance polarization in the absence of a magnetic field. As resonance polarization appears only in lines formed under non-LTE conditions, we need very good knowledge of the physical processes which play a role in the line formation. Furthermore resonance polarization is very sensitive to the anisotropy of the line radiation field, which is a higher order quantity as compared with the intensity
itself. Some processes affect more drastically the polarization than the intensity. This is the case for example for elastic collisions, partial frequency redistribution, velocity fields, and anisotropies in the solar atmosphere. Theoretical studies on the effects of velocity fields and anisotropies in the solar atmosphere should be done in the near future.

Let us note that until now only the polarization observed at line center has been used for Hanle effect diagnostics. The reason is that the observations have been performed with relatively low spectral resolution. The analysis of new observations should aim at the interpretation of the whole polarization profile. This would allow us to control the consistency of the results. Whenever possible several lines with different sensitivities to the Hanle effect should be used together. Several strong resonance lines, such as the Sr\,II line at 4078 Å and the Ba\,II line at 4554 Å, which are formed in the chromosphere, show significant resonance polarization. Photospheric lines sensitive to the Hanle effect are quite rare because collisions destroy the resonance polarization, except for lines with very strong oscillator strengths, such as the Sr\,I line.

References

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