On the Sr $\lambda$4607 Å Hanle depolarization signals in the quiet Sun

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Abstract. The Hanle depolarization signals of Sr $\lambda$4607 Å have been used to estimate the unsigned magnetic flux and magnetic energy existing in the quiet Sun photosphere. However, the Sr $\lambda$4607 Å Hanle signals are not sensitive to the unsigned flux and energy. They only bear information on the fraction of photosphere occupied by magnetic field strengths smaller than the Hanle saturation, which do not contribute to the unsigned flux and energy. We deduce an approximate expression for the relationship between magnetic fill factor and Hanle signal. When applied to existing Hanle depolarization measurements, it indicates that only 40% of the quiet Sun is filled by magnetic fields with a strength smaller than 60 G. The remaining 60% of the surface has field strengths above this limit. Such constraint will be needed to determine the distribution of magnetic field strengths existing in the quiet Sun.

Key words. polarization – Sun: magnetic fields – Sun: photosphere

1. Introduction

Most of the solar surface does not show significant polarization signals in the traditional magnetic field measurements. However, the magnetism of this so-called quiet Sun shows up as soon as the polarimetric sensitivity and the angular resolution exceed a threshold (e.g., Sánchez Almeida 2004, and references therein). Magnetic fields in the quiet Sun were discovered back in the seventies by Livingston & Harvey (1975) and Smithson (1975), but they experience a revival due to as soon as the polarimetric sensitivity and the angular resolution exceed a threshold (e.g., Sánchez Almeida 2004, and references therein). Magnetic fields in the quiet Sun were discovered back in the seventies by Livingston & Harvey (1975) and Smithson (1975), but they experience a revival due to

Field strengths larger than a few hundred G. The Hanle effect induced signals are most sensitive to magnetic field strengths larger than a few hundred G. The Hanle effect induced signals respond to field strengths smaller than this limit.

Due to the complexity of the fields, they have to be characterized in terms of probability density functions (PDFs). The magnetic field strength PDF is particularly useful. It gives the fraction of solar photosphere occupied by magnetic fields with a given field strength. The two first moments of this PDF provide the unsigned magnetic flux density and the magnetic energy density, respectively (e.g. Sánchez Almeida 2004). All these advances notwithstanding, the observational characterization of the quiet Sun fields is unsatisfactory. The complex topology of the fields makes all present measurements prone to severe bias, a fact that has to be acknowledged and fixed up before developing a reliable observational picture of quiet Sun magnetism.

A significant part of what we know about the weakest fields comes from the interpretation of the Hanle depolarization signals of Sr $\lambda$4607 Å (Stenflo 1982, Faurobert-Scholl 1993, Faurobert-Scholl et al. 1995, Stenflo et al. 1997, Faurobert et al. 2001). In particular, it has been recently shown that the observed Hanle depolarization signals of Sr $\lambda$4607 Å require an average field of 130 G and a magnetic energy density of $1.3 \cdot 10^3$ erg cm$^{-3}$ (Trujillo Bueno et al. 2004). However, this mean field exceeds the limit able to induce significant Hanle depolarization signal in this line ($\sim 100$ G; see § 3, or Faurobert et al. 2001). As we will discuss (§ 3), this seeming inconsistency results from an assumption which
turns out to be decisive to assign a mean field and a magnetic energy to the observed Hanle depolarization signals, namely, the shape of the PDF. Such PDF-dependence of the inference casts doubts on the results and, more importantly, it urges us to understand what is the true information provided by Sr $\lambda$ 4607 Å. Using a simplified (yet realistic) treatment of the radiative transfer, we explore the diagnostic content under the conditions to be expected in the quiet solar photosphere, with a mean field strength larger than the saturation field of the Hanle effect. As a result, we find that the Hanle signals are sensible only to the fill factor of magnetic fields below the Hanle saturation. They provide almost no constraint on the mean field strength and magnetic energy that may exist in the quiet Sun. This fact has to be taken into account when using information from Sr $\lambda$ 4607 Å to determine the PDF of the quiet Sun magnetic field strength.

The work is organized as follows: §2 lists the approximations used to carry out the Hanle depolarization syntheses. The degree of realism of this treatment is discussed in §2.2. The Hanle signals to be expected from an exponential PDF with a mean field of 130 G are analyzed in detail in §3. The actual diagnostic content of the Sr $\lambda$ 4607 Å Hanle signals is worked out in §4. An example of PDF with unbound magnetic flux and energy compatible with the observed Hanle signals is shown in §5. Finally, the way in which these results constrain the distribution of magnetic fields existing in the quiet Sun are discussed in §6.

### 2. Hanle depolarization of Sr $\lambda$ 4607 Å

#### 2.1. Basic properties and notation

The Hanle depolarization of Sr $\lambda$ 4607 Å can be expressed as

$$Q/Q_0 \approx W_B(B) = 1 - \frac{2}{5} \left( \frac{\gamma_H^2}{1 + \gamma_H^2} + \frac{4\gamma_H^2}{1 + 4\gamma_H^2} \right), \quad (1)$$

where $Q/Q_0$ is the ratio between the observed linear polarization $Q$ and the polarization if there were no magnetic field $Q_0$. The symbol $\gamma_H$ parameterizes the magnetic field of the microturbulent distribution of magnetic fields with random orientation and constant field strength $B$,

$$\gamma_H = B/B_H. \quad (2)$$

The so-called Hanle parameter $B_H$ scales linearly with the radiative transition rate plus the depolarizing collision rate, and it can be computed from the temperature and density according to the prescription in Faurobert et al. (2001, §3). The relationship (1) is an approximation that holds when the Hanle depolarization results from a single scattering (Stenflo, 1982; Landi Degl’Innocenti, 1985; Faurobert et al., 2001). It is a good approximation for this particular line in the quiet Sun (see §2.2 below). The depolarization $W_B(B)$ does not vary significantly with $B$ when $B \gg B_H$. This property is often referred to as the saturation of the Hanle signal, implying that the Hanle depolarization is not sensitive to fields much larger than $B_H$. Figure 1 shows $W_B(B)$ when $B_H = 47$ G. Note that the depolarization basically changes for $B > 100$ G or $2B_H$. The value for $B_H$ used above is typical of Sr $\lambda$ 4607 Å in the photospheric heights where the line is formed, say, from 200 km to 400 km above the base of the photosphere (Faurobert-Scholl et al., 1995), which also show how the range of heights contributing to Hanle signals does not depend very much on the heliocentric angle. Figure 6 shows $B_H$ as a function of height in a quiet Sun model atmosphere (Malby et al., 1986). Note that $B_H$ is smaller than 50 G above 250 km, where Sr $\lambda$ 4607 Å is formed.

![Fig. 1](image1.png)

**Fig. 1.** (a) Sr $\lambda$ 4607 Å Hanle depolarization signals versus magnetic field strength for $B_H$ typical of the upper photosphere of the quiet Sun. The depolarization signals have no significant contribution when $B$ is, say, larger than 100 G. (b) Exponential PDF with mean 130 G (the solid line). (c) Unsigned flux density per unit of magnetic field strength for the PDF shown in (b). (d) Magnetic energy density per unit of magnetic field strength. The dashed lines in (b), (c) and (d) represent $[W_B(B) - W_B(\infty)]$ scaled to fit in the plots.

![Fig. 2](image2.png)

**Fig. 2.** $B_H$ as a function of height in the atmosphere for the quiet Sun model atmosphere by Malby et al. (1986). Note that $B_H$ is smaller than 50 G above 250 km, where Sr $\lambda$ 4607 Å is formed.

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**References:**

- Faurobert et al. (2001)
- Stenflo (1982)
- Landi Degl’Innocenti (1985)
- Faurobert et al. (2001)
- Maltby et al. (1986)
- Faurobert-Scholl et al. (1995)
- Malby et al. (1986)
then the depolarization signal \( <Q/Q_0> \) equals the average depolarization factor (see \[\text{Landi Deel Innocent 1985, §3}],
\[
<Q/Q_0> \geq \int_0^\infty P(B)W_B(B)dB.
\] (3)

Since \( <Q/Q_0> \geq 0 \) when \( B \to \infty \), the actual range of polarizations sensitive to magnetic field strength variations is only a part of \( <Q/Q_0> \), namely,
\[
<Q/Q_0> = \int_0^\infty P(B)[W_B(B) - W_B(\infty)]dB.
\] (4)

where \( Q_\infty \) is the linear polarization signal to be expected if only fields larger than the Hanle saturation are present in the atmosphere. For these PDFs, \( P(B) \neq 0 \) only when \( W_B(B) \simeq W_B(\infty) \), so that
\[
<Q_\infty/Q_0> = \int_0^\infty P(B)W_B(\infty)dB = W_B(\infty) = 1/5.
\] (5)

Two particular cases are of special interest. They have been used to assign unsigned magnetic fluxes and magnetic energies from the quiet Sun Hanle depolarization signals in the quiet Sun. In the case that \( P(B) \) is a very narrow function of \( B \), namely,
\[
P(B) \neq 0 \text{ only when } |B - \tilde{B}| < \Delta B << B_H,
\] (6)

then
\[
<Q - Q_\infty/Q_0> \simeq \int_0^\infty P(B)[W_B(B) - W_B(\infty)]dB = W_B(\tilde{B}) - W_B(\infty).
\] (7)

The second case assumes \( P(B) \) to be an exponential function of mean \( B_0 \),
\[
P(B) = B_0^{-1} \exp(-B/B_0).
\] (8)

Then equation (4) admits a compact expression,
\[
<Q - Q_\infty/Q_0> \simeq \frac{2}{5} \left[ \left( \frac{B_H}{B_0} \right) f(B_H/B_0) + \left( \frac{B_H}{2B_0} \right) f(B_H/2B_0) \right].
\] (9)

with
\[
f(x) = \int_0^\infty \frac{\exp(-xy)}{1 + y^2} dy.
\] (10)

2.2. Accuracy of the single scattering approximation

The equations described in the previous section hold for a single scattering event. However, they are also a good representation of the Sr I 4607 Å Hanle signal when a more complete treatment of the radiative transfer is considered. \[\text{Faurobert et al. 2001], and they conclude that both approaches lead to the same } \bigtriangledown \text{ within the error bars of the observations. Trujillo Bueno et al. 2004 work out the Sr I 4607 Å Hanle depolarization in a realistic 3D hydrodynamic simulation, considering a 15 level Sr I atom and solving the NLTE problem in three dimensions. Equations (4) and (5) still provide magnetic fields in close agreement with the full calculation. The depolarization signal found by \[\text{Trujillo Bueno et al. 2004],}
\[
< Q/Q_0 > > = 0.41 \pm 0.04,
\] (11)

for \( 0.2 \leq \mu \leq 0.6 \) (\( \mu \) stands for the cosine of the heliocentric angle). In order to reproduce these observations, \[\text{Trujillo Bueno et al. 2004] need an exponential PDF with } B_0 = 130 \text{ G or, alternatively, a delta-function PDF with } \tilde{B} = 60 \text{ G. These values of } B_0 \text{ and } \tilde{B} \text{ also reproduce the observable under the single scattering approximation. Using } B_H = 47 \text{ G (which is the mean value in the atmospheric layers where the Sr I 4607 Å Hanle depolarization is formed), equation with } B_0 = 130 \text{ G leads to}
\[
< Q/Q_0 > > = 0.42.
\] (12)

In addition, one obtains exactly the same depolarization setting \( B = 57 \text{ G in equation (7).} \)

A comment is in order. The large differences between the mean field strengths deduced by \[\text{Faurobert et al. 2001, } \tilde{B} 
\sim 25 \text{ G and Trujillo Bueno et al. 2004, } B = 60 \text{ G are not due the different ways in which they synthesize the Hanle depolarization } < Q/Q_0 > \text{ in terms of a turbulent magnetic field. This step of the estimate seems to be independent of the details of the modeling, and it is properly described by equation (4). The differences are due to the estimate of the scattering signals to be expected for no magnetic field (i.e., the quantity } < Q >. \text{ Although they start off from similar observed } < Q >, \text{ Faurobert et al. 2001 infer } < Q/Q_0 > > = 0.6 \text{ instead of the depolarization in equation (11). If Trujillo Bueno et al. 2004 would have found } < Q/Q_0 > > = 0.6, \text{ their treatment would have assigned } \tilde{B} \simeq 30 \text{ G to this signal. Such conclusion can be readily inferred from their Fig. 1 by artificially increasing the observed } < Q > \text{ to yield } < Q/Q_0 > > = 0.6. \text{ (See also Shchukina & Trujillo Bueno 2003).} \]

3. Largest field strength contributing to the Hanle signals

This section analyzes in detail the case of an exponential PDF with \( B_0 = 130 \text{ G. It illustrates the difficulties to infer unsigned magnetic fluxes and energies from the quiet Sun Hanle depolarization signals of Sr I 4607 Å.} \)

Let us define \( B_{\text{max}} \) as the largest field strength that produces a significant contribution to the observed signal. The contribution would be regarded as significant only if it is above the observational error \( \epsilon \). Then \( B_{\text{max}} \) is defined as
\[
\epsilon = \frac{\int_0^{B_{\text{max}}} P(B)[W_B(B) - W_B(\infty)]dB}{\int_0^\infty P(B)[W_B(B) - W_B(\infty)]dB},
\] (13)

which follows from equation (3) and the condition that all magnetic fields with \( B > B_{\text{max}} \) change the depolarization by less than a factor \( \epsilon \). Figure 4, the solid line, shows \( \epsilon = \epsilon(B_{\text{max}}) \) when

\[\text{The estimate by Trujillo Bueno et al. 2004, is to be favored for quiet Sun diagnosis since it is based on realistic MHD simulations, 3D scattering polarization calculations, and a complex Sr atom.}\]
Fig. 3. Relative errors of the Hanle depolarization signals produced by neglecting all magnetic fields larger $B_{\text{max}}$ (the solid line). It is smaller than the 10% observational error when $B_{\text{max}} > 87$ G. Relative contribution to the unsigned magnetic flux density (the dashed line) produced by magnetic fields larger than $B_{\text{max}}$.

$B_H = 47$ G and $B_0 = 130$ G, i.e., the parameters that characterize the observed depolarization. The true observational error is larger than 10% (see §2). Note that $\epsilon < 0.1$ when $B_{\text{max}} \geq 100$ G, meaning that those magnetic fields of the exponential PDF with $B > 100$ G do not contribute to the observed signal.

The unsigned magnetic flux density and magnetic energy density can be computed from the first two moments of the PDF (e.g., Sánchez Almeida 2004). However, the magnetic fields that determine the first two moments of an exponential PDF with $B_0 = 130$ G exceed $B_{\text{max}} \approx 100$ G. Consequently, the unsigned flux and the energy assigned assuming an exponential PDF are not constrained by the observations. The first two moments are given by

$$< B > = \int_0^\infty B \cdot P(B) dB,$$

and

$$< B^2 > = \int_0^\infty B^2 \cdot P(B) dB.$$  \hspace{1cm} (14)  \hspace{1cm} (15)

The integrands of equations (14) and (15) describe the contribution of each field strength to the two moments, and they are shown in Figs. 11 and 11. The figures include a scaled version of $[W_B(B) - W_B(\infty)]$ (the dashed lines), which indicates the range of field strengths constrained by the observations. Obviously, most of the unsigned flux (related to the first moment) and energy density (second moment) are provided by field strengths larger than 100 G. It is possible to quantify the bias defining the fraction of unsigned flux density made up by considering field strengths which do not contribute to the Hanle signals, explicitly,

$$\delta < B > = \frac{\int_{B_{\text{max}}}^\infty B \cdot P(B) dB}{\int_0^\infty B \cdot P(B) dB},$$

Similarly, the fraction of energy density that comes from the tail of the PDF, and so, it does not contribute to the Hanle signals, is

$$\delta < B^2 > = \frac{\int_{B_{\text{max}}}^\infty B^2 \cdot P(B) dB}{\int_0^\infty B^2 \cdot P(B) dB}.$$  \hspace{1cm} (17)

Both $\delta < B >$ and $\delta < B^2 >$ are shown in Fig 3. It turns out that 90% of the Hanle signals ($\epsilon = 0.1$) are produced by $B < 86$ G. The tail of magnetic fields which do not contribute to the Hanle signals actually produce 86% of $< B >$ and 97% of $< B^2 >$.

In other words, the result by Trujillo Bueno et al. (2004) that $< B > = B_0 = 130$ G and $< B^2 > / (8\pi) = (2B_0^2)/(8\pi) = 1.3 \cdot 10^3$ erg cm$^{-3}$ is based on the assumption of the shape of PDF, but it is not constrained by the observations. By changing the tail of large field strengths of the PDF one can modify in an arbitrary manner the unsigned flux and energy, yet producing the observed Hanle depolarization. A bold example is given in §5.

4. What does the Hanle depolarization of Sr I 4607 Å diagnose?

Let us consider PDFs with the properties to be expected for the solar quiet Sun magnetic fields. The Hanle signals are produced by magnetic fields within the bandpass where $[W_B(B) - W_B(\infty)] \neq 0$, which is of the order of $2B_H$. Then the Hanle signals can be estimated as

$$\langle Q - Q_0 \rangle / Q_0 \approx \int_0^{2B_H} P(B)[W_B(B) - W_B(\infty)] dB.$$  \hspace{1cm} (18)

In addition, the quiet Sun PDF should spread out over a range of field strength larger than $B_H$ (see, e.g., Sánchez Almeida 2004), so that within the bandpass of interest, it can be approximated by a linear expansion,

$$P(B) = a + b(B - B').$$  \hspace{1cm} (19)

Obviously,

$$a = \frac{1}{2B'} \int_0^{2B'} P(B) dB.$$  \hspace{1cm} (20)

If one chooses $B'$ to be

$$B' = \frac{\int_0^{2B_H} B[W_B(B) - W_B(\infty)] dB}{\int_0^{2B_H}[W_B(B) - W_B(\infty)] dB},$$

then the Hanle depolarization signals given by equation (18) are independent of the slope $b$,

$$\langle Q - Q_0 \rangle / Q_0 = C \int_0^{2B'} P(B) dB,$$  \hspace{1cm} (21)

$$C = \frac{1}{2B'} \int_0^{2B_H} [W_B(B) - W_B(\infty)] dB.$$  \hspace{1cm} (22)

The integrals defining $B'$ and $C$ can be solved analytically to render

$$B' \approx 0.65 B_H, \ C \approx 0.54,$$  \hspace{1cm} (23)
and, consequently,
\[
< \frac{Q - Q_\infty}{Q_0} >= 0.54 \int_0^{1.3B_H} P(B)dB.
\]  
(24)

The Hanle depolarization signals scale with the fill factor of fields with strength smaller than 1.3B_H. As expected, the Hanle depolarization of Sr I 4607 Å is independent of the actual unsigned magnetic flux or magnetic energy of the distribution.

The approximate equation (24) has been tested for the case where \( P(B) \) is exponential. Figure 4(a) shows the variation of the Hanle depolarization signals with \( B_H/ < B > \), where \( < B > \) stands for the mean magnetic field of the distribution. The solid line has been computed from the exact solution (2), whereas the dashed line follows from the approximate equation (24). The agreement is good, and it improves to excellent if \( C = 0.58 \) (the dotted line). Figure 4(b) also shows the exact and the approximate Hanle signals deduced for the numerical turbulent dynamo PDF used in Sánchez Almeida et al. (2003). The agreement of the approximation is also satisfactory. Despite the simplistic approximation leading to the relationship (24), it reproduces within 10% the exact relationship (2). The agreement is expected independently of the (unknown) details of the quiet Sun PDF, since equation (24) it is based on very general assumptions.

Equation (24) satisfies the observation (11) when magnetic field strengths smaller than 60 G occupy 40% of the quiet Sun. Obviously, the exponential PDF chosen by Trujillo Bueno et al. (2003) fulfills this criterion. The turbulent dynamo PDF used by Sánchez Almeida et al. (2003) § 5) does it too.

5. Example of unbound magnetic flux and energy compatible with the observed Hanle signals

From the arguments spelled out above, it is clear that the unsigned magnetic flux and energy of the distribution are not related to the Hanle signals. This section shows and example reinforcing the point. We show a PDF producing the observed polarization with an arbitrarily large magnetic flux and energy.

Consider the combination of exponentials,
\[
P(B) = \beta B_1^{-1} \exp(-B/B_1) + (1 - \beta)B_2^{-1} \exp(-B/B_2),
\]  
(25)

with \( B_1 << B_H << B_2 \). The second exponential do not contribute to the Hanle depolarization signals, since it is given by equation (2) with \( B_H/B_2 \to 0 \). On the other hand, \( f(x) \to x^{-1} \) when \( x \to \infty \), which together with equations (9) and (5) lead to
\[
< Q/Q_0 > \simeq (1 + 4\beta)/5.
\]  
(26)

The value \( \beta \approx 0.27 \) satisfies the observed depolarization (11). On the other hand, the two moments (14) and (15) only depend on the second component,
\[
< B > = \beta B_1 + (1 - \beta)B_2 \simeq (1 - \beta)B_2,
\]  
(27)

\[
< B^2 > = 2\beta B_1^2 + 2(1 - \beta)B_2^2 \simeq 2(1 - \beta)B_2^2,
\]  
(28)

since \( B_1 << B_2 \). Then the unsigned flux and the energy corresponding to equation (25) can be arbitrarily large by increasing \( B_2 \) with no modification of the Hanle signals (equation (26)).

6. Conclusions

The Hanle depolarization signals of Sr I 4607 Å are insensitive to the magnetic flux and magnetic energy existing in the quiet Sun photosphere. They only bear information on fraction of surface occupied by magnetic field strengths smaller than some 2B_H, equivalent to 100 G when the so-called Hanle parameter \( B_H \) is 50 G. In order to gain physical insight into the diagnostic provided by the Sr I 4607 Å Hanle depolarization signals, we estimate the signals to be expected when the magnetic atmosphere contains disorganized magnetic fields with field strengths spanning from zero to a value exceeding \( B_H \). The expected signal is given by equation (24). It is a fixed fraction (54%) of the fill factor of magnetic fields whose strengths are smaller than 1.3 B_H.
Our result implies that the findings by Trujillo Bueno et al. (2004) have to be updated, in particular, the Hanle depolarization signals that they work out (equation [12]) do not imply an unsigned flux and a magnetic energy density. They imply that 40% of the quiet Sun is covered by fields whose strength is smaller than 60 G. In other words, some 60% of the quiet Sun has field strengths larger than 60 G. Obviously, this result is consistent with a distribution of magnetic fields having a magnetic flux and energy even larger than those inferred by Trujillo Bueno et al. (2004), but the unsigned flux and energy are not constrained by the Hanle signals. The magnetic flux and energy are constrained by the polarization signals induced via Zeeman effect, which contain information on the hG and kG field strengths of the quiet Sun PDF (e.g., Sánchez Almeida & Lites 2000). For example, the magnetic energy density of the kG fields observed by Domínguez Cerdeña et al. (2003), which occupy only 2% of the surface, actually contain as much energy as an exponential PDF with $B_0 = 130 \, \text{G}$.

We lack of a reliable quiet Sun PDF to represent the whole range of observed field strengths from zero to two kG. This PDF would have to be assembled piecing together information from various sources, as it is indicated in Sánchez Almeida (2004). The results of our analysis are needed to complete such observational work, since they clarify how the Sr $\text{i} \lambda 4607$ Å Hanle signals constrain the empirical PDF.

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