New possibilities for the diagnostics of solar magnetic fields

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PLEASE SCROLL DOWN FOR ARTICLE
NEW POSSIBILITIES FOR THE DIAGNOSTICS OF SOLAR MAGNETIC FIELDS

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The polarized spectrum that is produced by coherent scattering processes has a structural richness comparable to that of the intensity spectrum but different in appearance and physical origin. The amplitudes of the polarization features are influenced by magnetic fields via the Hanle effect in a way that is very different from the ordinary Zeeman effect. While the main contribution to Zeeman-effect observations comes from the strong fields of the photospheric magnetic flux tubes, the Hanle effect is sensitive to weak magnetic fields, turbulent fields of mixed polarities, and chromospheric fields. As different spectral lines respond very differently to the Hanle effect, the scattering polarization offers novel and rich diagnostic opportunities. In the present overview we illustrate some of these new effects and indicate what can be learnt from them.

KEY WORDS Sun -- magnetic fields -- polarimetry -- Hanle effect

1 WHY ARE NEW DIAGNOSTIC METHODS NEEDED?

Since it was first introduced in astrophysics by Hale (1908), the Zeeman effect has allowed us to map the Sun's magnetic field in great detail. Polarimetric observations in combinations of Zeeman-sensitive lines have revealed that solar magnetic fields have a highly intermittent structure at scales beyond the spatial resolution limit of the observations. Taking advantage of differential effects in the non-linear polarimetric response of the Zeeman effect in different spectral lines it has been possible to extract information about field strengths and thermodynamics at scales beyond the telescope resolution (Stenflo, 1973, 1994). As these are the scales at which most of the magnetic flux resides, one needs to interpret the polarimetric Zeeman-effect data in terms of models for the magnetic field. A consistent picture has emerged in terms of strong-field magnetic flux tubes, which cover on average only about one percent of the solar surface. Inversion of Stokes spectra has led to the construction of flux tube models at increasing levels of sophistication (Solanki, 1993; Nagendra and Stenflo, 1999).

This flux tube picture is however incomplete and unsatisfactory, since it leaves us with a detailed description of 1% of the photosphere while providing few clues
concerning the magnetic properties of the remaining 99%. For simplicity the volume surrounding the flux tubes is usually assumed to be field free, an idealization that can have little to do with the actual state of the highly conducting solar plasma.

The reason for this state of affairs is that the Zeeman effect fails to deliver much information about 99% of the photosphere. Almost all Zeeman-effect diagnostics, with few exceptions, are done with photospheric spectral lines. In chromospheric lines the Zeeman splitting is generally much smaller than the line width and provides information that is mainly limited to magnetic flux. The Zeeman effect is insensitive to magnetic fields that are weak, like the fields between the flux tubes or the fields...
Figure 1 Example of the structural richness of the second solar spectrum with molecular contributions and anomalous polarization effects. The recordings were made with ZIMPOL at Kitt Peak near the solar north pole on April 4, 1995 (Stenflo, Keller, and Gandorfer, 2000). The linearly polarized spectrum are very different from the processes that produce the structures in the intensity spectrum, the term 'second solar spectrum' has been introduced (Ivanov, 1991) to stress that we are dealing with a new type of spectrum with complementary information.

An atlas of the second solar spectrum for the quiet Sun has recently been completed by Gandorfer (2000) with ZIMPOL and the telescope at IRSOL (Istituto Ricerche Solari Locarno). Selected portions of the spectrum have been explored in greater detail with ZIMPOL at Kitt Peak. Figure 1 shows examples of spectral sections around the strong MgI lines at 5167, 5173, and 5184Å. One striking property of these recordings is the prominence of molecular contributions (here due to MgH), although the molecular lines are very weak and inconspicuous in the intensity spectrum. Attempts have been made to model the molecular lines with polarized radiative transfer (Mohan Rao and Rangaradjan, 1999), but it is not yet sufficiently understood why they are so prominent in the polarized spectrum.

The intrinsic polarizability of a scattering transition depends on the quantum numbers of the atomic levels involved. Usually the polarizability is given by the parameter $\eta_2$, which represents the fraction of the scattering processes that behave like polarizing, classical dipole-type scattering. The remaining fraction, $1 - \eta_2$, behaves like isotropic, unpolarized scattering. This characterization assumes that the initial atomic state of the scattering transition has no atomic polarization (alignment), and that there is no coherency transfer from other atomic levels to the ones involved in the considered scattering transition.

When these polarizability concepts are applied to understand what we see in the second solar spectrum we frequently find strikingly anomalous behavior (Stenflo, Keller, and Gandorfer, 2000).
Keller, and Gandorfer, 2000). Figure 1 is an example of this. Although $W_2$ for the MgI 5184Å line is two orders of magnitude smaller than that of the MgI 5167Å line, and we expect the observed polarization amplitudes to scale with $W_2$, we see in Figure 1 that the observed amplitude in the 5184Å line is larger than that of the 5167Å line. The situation is not much improved when we account for all the fluorescent transitions that can occur within the multiplet (i.e., when the initial and final states of the scattering transition are not the same). According to these concepts, the 5184Å line should always show a much smaller polarization than the other lines, but this is not what we see here.

Through such examples it has become increasingly clear that the interpretative framework has to be enlarged to include the possibility of initial-state atomic polarization produced by coherency transfer from the excited state in a process called optical depopulation pumping (Trujillo Bueno and Landi Degl'Innocenti, 1997; Landi Degl'Innocenti, 1998, 1999). The excited state acquires atomic polarization from the anisotropic, radiative excitation. The spontaneous emission process transfers some of the alignment to the lower state. With many such processes a statistical equilibrium with a polarized lower level is reached. Scattering from a polarized initial state produces very different polarization in the emitted radiation as compared with scattering from an unpolarized state.

**SIGNATURES OF THE ZEEMAN AND HANLE EFFECTS**

The Zeeman effect generates its characteristic polarization signatures regardless of whether the spectral line has been formed by coherent or incoherent processes. It is not dependent on any scattering geometry, so it can be recorded with similar amplitudes all over the solar disk. The Hanle effect on the other hand only operates on polarization that is produced by coherent scattering. The effects of the magnetic fields on this scattering polarization is what the term 'Hanle effect' refers to. It manifests itself primarily in two ways: depolarization and rotation of the plane of linear polarization. As mentioned before, it is best observable in a limb zone. In the non-magnetic case the scattering polarization is linear with the plane of polarization usually oriented parallel to the nearest limb. In all our observational examples here the Stokes $Q$ direction is defined as the direction parallel to the nearest solar limb. Then Hanle depolarization suppresses the amplitude of $Q$, while Hanle rotation generates a signal in Stokes $U$ (which would be zero in the absence of magnetic fields).

In strong lines with pronounced damping wings there is usually appreciable scattering polarization in both the core and wings. It is a characteristic and distinguishing property of the Hanle effect that it only operates in the Doppler cores of the lines but not in the wings.

While the polarization signals from the Zeeman effect depend on the ratio between the Zeeman splitting and the Doppler width of the line, the Hanle effect depends on the ratio between the Zeeman splitting and the damping width (inverse life time of the atomic state). Since the damping width is much smaller than the...
Figure 2 Example of the coexistence between scattering polarization (in Q/I in the SrI 4607A line) and the transverse and longitudinal Zeeman effect. The recording was made with ZIMPOL at NSO/Kitt Peak on March 4, 2000, near the SW limb (at $p = 0.07$), where there was some minor facular activity.

Doppler width, the Hanle effect responds to magnetic fields in a much weaker field-strength regime than the Zeeman effect. Usually the term 'Hanle effect' refers to this weak-field regime. As the field strength increases, there is a gradual transition to the ordinary Zeeman effect regime, with a poorly explored 'mixed Hanle-Zeeman' regime of intermediately strong fields in between. The observations indicate that the Hanle and Zeeman effects keep their qualitatively distinct signatures even in the transition between weak and strong fields. What we see is that the Hanle signatures fade out while the Zeeman signatures take over.

Figure 2 gives an example of the Hanle and Zeeman signatures side by side. In the spectral range shown it is only the SrI 4607A line that exhibits scattering polarization, manifested as the bright 'emission' feature in the upper portion of the Q/I diagram. The other lines in the range appear weakly dark in Q/I, meaning that they depolarize the continuum polarization. In the lower portion of the Q/I diagram we enter a region where the transverse Zeeman effect tends to dominate over the scattering polarization in the Sr line. In all the other lines we see the characteristic...
symmetrical signature of the transverse Zeeman effect with the polarization maxima of the $\sigma$ components in the line wings. The same signature is seen in the $U/I$ diagram. In addition, we see in the SrI line in the top and bottom part of the $U/I$ diagram a hint of a single-peak core signal, which may be understood in terms of some Hanle rotation of $Q$ into $U$. The $V/I$ diagram is exclusively characterized by the anti-symmetric profile signatures of the longitudinal Zeeman effect.

We have found it to be typical for the behavior of the SrI 4607 Å line that its scattering polarization exhibits very little spatial variation (for constant limb distance) of the Hanle depolarization and very little of the Hanle rotation effect. Still comparison between radiative-transfer modelling of this line and observations (Faurobert-Scholl, 1993) shows that the average polarization amplitude has been suppressed by a Hanle depolarization that would occur if there is a turbulent magnetic field of mixed polarities and a strength of about 10G. For an isotropic distribution of field vectors within the spatial resolution element there is no net orientation of such a field and therefore no net Hanle rotation.
In contrast the NaI D₂ 5890Å line, which is formed in the lower chromosphere, often exhibits large spatial variations of its Hanle effect, as illustrated in Figure 3. The scattering polarization in Q/I in the D₂ line has a narrow peak in the Doppler core, surrounded by broad maxima in the line wings (the diffuse and broad bright bands in the Q/I diagram). In U/I there is no wing polarization. The spatial fluctuations along the slit occur exclusively in the Doppler core for both Q/I and U/I. This behavior is exactly what we expect from the Hanle effect, which only affects the line core but not the wings. The fluctuations seen in Q/I can thus be understood in terms of Hanle depolarization due to spatially varying chromospheric magnetic fields, while the fluctuating signal in U/I is due to spatially varying Hanle rotation. Note that the fluctuations in Q/I and U/I are fairly uncorrelated, which is natural since the Hanle depolarization and rotation have different functional dependencies on the field orientation and strength. The V/I diagram is as always purely a domain of the longitudinal Zeeman effect.

4 CHROMOSPHERIC FIELD GEOMETRY FROM LOWER-LEVEL ATOMIC POLARIZATION

The scattering polarization across the NaI D₂ and D₁ lines that we showed in Figure 3 has long remained enigmatic and a fascinating challenge for quantum and
Figure 4 The scattering polarization observed in April 1995 with ZIMPOL across the NaI D₂ and D₁ lines (Stenflo and Keller, 1997) (thin solid curves) is modelled taking quantum interference between the \( J = \frac{3}{2} \) and \( \frac{1}{2} \) excited states into account (thick solid curve), while the dashed curve shows what happens when the interference term is omitted (Stenflo, 1997). While this model, which ignores hyperfine structure splitting and lower-level atomic polarization, can reproduce the wing polarization very well, it is unable to account for the narrow polarization peaks in the Doppler cores.

The range of field strengths for which the Hanle effect has its main sensitivity scales with the ratio between the Larmor precession period and the life time of the atomic state that is involved. As the ground state has such a long lifetime (in comparison with the excited states), Hanle depolarization in the ground state sets in already in the mG range of field strengths. Since it is unlikely that we will encounter such weak fields anywhere in the highly electrically conductive solar atmosphere, we will always be in the saturated Hanle regime when the scattering polarization is due to atomic polarization in the ground state, as it apparently must be for the D₁ line. Hanle saturation however does not imply that the polarization must vanish due to Hanle depolarization. Although there is no longer any field-strength dependence for the polarization in the Hanle saturated regime, the amount of depolarization depends on the orientation of the field and the scattering geometry according to rather complex trigonometric relations. In particular there is no depolarization at all when the illumination of the scattering particle is symmetric around the magnetic field vector, which is the case for a vertical orientation of the magnetic field (since the anisotropic illumination is predominantly due to the limb darkening).
From such theoretical considerations it follows that the observed core polarization peak in the D$_1$ line can only exist and survive if the magnetic field in the observed solar region is nearly vertical. Since the D$_1$ line is formed in the lower chromosphere, and core polarization in D$_1$ is almost always seen in quiet solar regions (but not much in magnetically more active regions like the one in Figure 3), we are led to the conclusion that the typical orientation of the magnetic field in quiet regions is vertical. This conclusion apparently contradicts the previous paradigm that chromospheric fields are largely horizontal with a canopy structure (Giovanelli, 1980; Jones and Giovanelli, 1983). With horizontal fields there is no known way to explain the existence of the D$_1$ core polarization peak.

The core peak of the D$_2$ line does not have to be produced by lower-level atomic polarization, since the D$_2$ transition is intrinsically polarizable without this phenomenon. For D$_2$ it is rather the triplet profile shape of the core and wing peaks that presents the interpretational challenge. If the D$_2$ core peak were due to lower-level atomic polarization, then the Hanle-effect fluctuations of the peak amplitudes in the D$_2$ and D$_1$ lines would be closely correlated. Observations (Stenflo et al., 2000) in weakly active facular regions near the limb show that this is not the case, as expected if the D$_2$ and D$_1$ lines belong to two entirely different Hanle regimes. This indicates that the D$_2$ core polarization is governed by the excited state life time and polarization and therefore is in the non-saturated Hanle regime. The observed distribution functions for the Hanle effect in the weak facular regions can be understood reasonably well in terms of an isotropic angular distribution of the field orientations and a field strength of about 4 G (Stenflo et al., 2001).
step, starting with idealized models. Nevertheless the Hanle effect has already given us new insights about turbulent and chromospheric magnetic fields not possible to obtain via the Zeeman effect.

Observationally this new diagnostic territory can only be explored with highly sensitive imaging polarimeters, with which the polarimetric accuracy is only determined by photon statistics. The resulting accuracy then depends on the light-gathering power of the telescope. Even with the largest solar telescopes one needs to make major trade-offs between the four parameters polarimetric accuracy and spatial, spectral, and temporal resolutions (Stenflo, 1999). Instrumental polarization that leads to cross talk between the Stokes parameters is another major concern in vector polarimetry. In the design of future solar telescopes one therefore strives for the largest possible aperture and for minimal or constant instrumental polarization.

References