Solar Magnetic Field Diagnostics with the Molecular Hanle Effect

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Abstract. Weak entangled magnetic fields with mixed polarity occupy the main part of the quiet solar photosphere. While the Zeeman effect diagnostics fail to measure such fields due to cancellation in polarization, the Hanle effect, accessible through the second solar spectrum, provides us with a very sensitive tool for studying the distribution of weak magnetic fields on the Sun. Molecular lines are valuable for magnetic field diagnostics thanks to their broad range of magnetic sensitivities within narrow spectral regions, so that the differential Hanle effect can be employed, which greatly reduces the model dependence of deduced magnetic field strengths. Here we present our recent results on the diagnostic of solar turbulent magnetic fields with the help of CN transitions in the violet system. In addition, we have implemented modeling of coherent scattering in molecular lines into a non-LTE radiative transfer code. Together with the Hanle effect theory this provides us with a realistic model for studying turbulent magnetic fields.

1. Introduction

The understanding of the solar magnetic field is one of the key points of modern solar physics. Zeeman effect diagnostics allow measuring only a small fraction of the fractal-like structured magnetic field (Stenflo & Holzreuter 2003). However the main part of the atmosphere is filled by entangled fields with mixed polarity, which remain inaccessible due to cancellation of the polarimetric signal (Trujillo Bueno et al. 2004). Such hidden magnetic fields can be measured with the Hanle effect which results in a modification of coherent scattering processes and usually leads to a reduction and rotation of the line polarization as compared to the non-magnetic case. As the Hanle effect alters the scattering process it can be only accessed through the spectrum formed by coherent scattering, which is called the “second solar spectrum” (Ivanov 1991) due to its richness and significance.

Scattering in molecular lines plays an important role in forming the second solar spectrum and even dominates in some spectral regions. The sensitivity of molecular lines to the Hanle effect significantly varies with the total angular momentum of the upper level \( J \). As a narrow spectral region can contain lines with quite different \( J \) values this allows to employ the differential Hanle effect (cf. Stenflo et al. 1998; Trujillo Bueno 2003; Berdyugina & Fluri 2004). Moreover, due to the large temperature sensitivity different molecules sample different rather narrow layers of the solar atmosphere. Moreover, combined
with chromospheric atomic Hanle effect, which is well established since the work by Faurobert-Scholl (1992), molecular Hanle effect provides us with a possibility to study a 3-dimensional structure of the entangled solar magnetic field. In this paper we present a brief overview of our results based on modeling of the Hanle effect in the CN violet system.

2. The Hanle Effect in the CN Violet System

The upper and lower states of the CN violet system are both doublet states with relatively small fine structure splitting. Therefore, for calculating the Mueller matrix of the scattering process quantum interferences between different fine structure components (Stenflo 1997) as well as the Paschen-Back effect (PBE) on the fine structure (Schadee 1978; Berdyugina et al. 2005; Asensio Ramos & Trujillo Bueno 2006) have to be taken into account. The influence of these effects on the Hanle effect in the CN violet system was described by Shapiro et al. (2007b).

The interferences between fine structure components mainly result in the line core depolarization as compared with the wing polarization. This depolarization appears due to gradual disappearance of the interference between different fine structure transitions. This is analogous to the Hanle effect, when decreasing interferences between different magnetic subcomponents in a magnetic field also cause the depolarization in the line core. The PBE significantly changes the scattering profiles of lines with small angular momenta for a magnetic field stronger than about 100 G. However, in the wings the polarization approaches the zero-field value, in agreement with the principle of spectroscopic stability. The PBE changes also the net polarization properties.

The net depolarization can be characterized by the integrated quantity:

$$W_{\text{tot}}(B) = \frac{\int Q(\lambda)d\lambda}{\int I(\lambda)d\lambda} \frac{\int Q(\lambda)d\lambda}{(Q/I)_{\text{wings}}}.$$  

(1)

The main contribution to the integral in the numerator comes from the line core and in case of the rectangular profile approximation Eq. (1) gives the ratio between the core and wing polarization. In the Zeeman regime (ZR) the net depolarization $W_{\text{tot}}(B)$ is decreasing with the magnetic field strength $B$. When magnetic splitting is significantly larger than the level’s natural width, $W_{\text{tot}}(B)$ becomes independent on the magnetic field (the so-called saturated Hanle effect). In Fig. 1 we present the dependence of the saturated net depolarization on the magnetic field strength for several doublet lines and for two cases of the magnetic field direction. All curves in these figures are valid only for fields stronger than about 10 G, since for weaker fields the Hanle effect is not saturated. The PBE significantly affects the value of the saturated net depolarization, while in the Zeeman regime it remains constants. Note that in a vertical field the depolarization for all transitions asymptotically approaches unity with increasing field strength, while for a horizontal field the asymptotic values are different for the different lines.
3. The CN Violet System in the Second Solar Spectrum

The CN violet system is a prominent feature of the second solar spectrum. As a first try of interpretation we employ a simple radiative transfer model. In this model we assume that an isothermal and homogeneous CN molecular layer is situated above the region where the continuum radiation is formed. Its lower boundary is irradiated by the incident solar continuum radiation, which in our model is independent on azimuth and obeys to the analytical limb-darkening law from Neckel (1996). We have taken the value of the continuum polarization from Stenflo (2005) for $\mu = 1$ and expand it for arbitrary $\mu$-values with the help of the analytical expression from Fluri & Stenflo (1999). While passing through the molecular layer this initial incident radiation can be either scattered or absorbed by CN molecules. Due to their intrinsic polarizability the CN lines are seen as emission lines in the second solar spectrum. The magnetic field affects the strength of these lines via the Hanle effect and depolarizes them.

The crucial point here is that first three free parameters ($T_{\text{eff}}$, $c_{\text{sc}}$, and $T_{\text{norm}}$) affect all lines in approximately the same way, while the line Hanle depolarization due to the magnetic field is a decreasing function of the upper level total angular momentum $J$. This differential behavior of the depolarization allows...
Figure 2. Fits to observations (thin solid lines) of the CN violet system in a wavelength region close to the (0,0) band head. The magnetic field strengths in the modeled spectra were set to 0 G (no depolarization, dashed line), 11 G (best fit, thick solid line), and 25 G (too much depolarization, dotted line). Labels at the bottom of the lower panel indicate the CN doublets with the N quantum numbers of the lower states. The labels at the top of the lower panel indicate the wavelength points chosen for the fitting procedure. From Shapiro et al. (2007a).

Figure 3. $\chi^2$–contours for the fit shown in Fig. 2. The panels show 2-dimensional cuts in the parameter space through the normalized $\chi^2_{\text{min}} = 1.66$. Numbers on the contours indicate the values of $\chi^2$ as defined in Eq. (2). From Shapiro et al. (2007a).

us to distinguish the impact of the Hanle effect from influences of all other free parameters and hence to determine the magnetic field strength. We have chosen several narrow spectral regions containing lines with both small and large $J$, which are ideal for applying the differential Hanle effect technique. In Fig. 2 we present the example of a fit to the observations from
the atlas compiled by Gandorfer (2005) in the region near the (0,0) band head, containing a mixture of lines with $N \sim 10$ and $N \sim 40$ from the P branch (for more examples see Shapiro et al. 2007a). Applying the magnetic field of 11 G influences mainly the lines with $N \sim 10$ and can fit the observed $Q/I_c$ profile, while other lines with high $J$ numbers remain unaltered. This is a good example of the differential Hanle effect diagnostics: the magnetic field has to be strong enough to depolarize the highly sensitive doublets with $N \sim 10$, but it should not be too strong to cause depolarization of the doublets with $N \sim 40$.

The magnetic field strength found in this region is significantly weaker than values determined for the other regions (about 20 G, see Shapiro et al. 2007a). It can be connected with the fact that the analyzed data were not observed simultaneously and sampled in principle different spatial positions on the Sun. Moreover, this region contains lines from the (0,0) band with moderate $J$ values which are the strongest in the CN violet system. So these lines form higher in the atmosphere, and our results suggest that the magnetic field strength may decrease with height. However, a detailed interpretation of these small differences lies outside the scope of the current model.

To describe the accuracy of the fit and constrain the free model parameter we calculate the quantity

$$\chi^2 = \frac{\zeta}{n} \sum_{i=1}^{n} \frac{\left(\frac{Q/I_c}{I_c}\right)_{\text{obs}} - \left(\frac{Q/I_c}{I_c}\right)_{\text{th}}}{\sigma_{Q/I_c}}^2 + \frac{1 - \zeta}{n} \sum_{i=1}^{n} \frac{\left(\frac{I/I_c}{I_c}\right)_{\text{obs}} - \left(\frac{I/I_c}{I_c}\right)_{\text{th}}}{\sigma_{I/I_c}}^2, \quad (2)$$

where $n$ is the number of data points and $\sigma_{Q/I_c}$ and $\sigma_{I/I_c}$ are the absolute errors of the observed polarization and intensity, which we set to 0.008% and 0.005%, respectively. The coefficient $\zeta$ allows us to give larger weight either to the intensity or polarization fit. We adopt here $\zeta = 7/8$, but the result of the fitting procedure is almost independent on the assumed value.

Figure 3 displays the accuracy of the fitted spectrum illustrated by $\chi^2$-contours in the parameter space. It also shows that the magnetic field is quite well constrained by the observations. We emphasize again that this is a direct consequence of the differential Hanle effect behavior.

4. NLTE Radiative Transfer Model

Despite the quite successful fit in several spectral regions, our simple model fails to fit strong CN lines, for example the (0,0) band head. Moreover, it is not possible to self-consistently interpret the differences in the deduced model parameters obtained in the different spectral regions. To solve this problems we developed a new, more self-consistent model of the 1D polarized radiation transfer.

We employ the numerical NLTE code (hereafter RH-code) written by Uitenbroek (2001) and based on the multilevel accelerated lambda iterations (MALI) method (cf. Rybicki & Hummer 1991, 1992). We have included calculations of electronic-vibrational molecular transitions into this code. The statistical
equilibrium equations in the RH-code are solved under the assumption of LTE populations within a single vibrational level since it would be time-consuming to solve them for each individual vibrational-rotational level (as we have to deal with more than 2000 transitions simultaneously). With the RH-code we compute opacities and intensity, neglecting polarization. Afterward we use them as the input for the second code written by Fluri & Stenflo (2003) and Fluri et al. (2003) which iteratively calculates polarization, assuming that opacities obtained in the RH-code remain unchanged (which is a good approximation since the degree of polarization is always smaller than 1%). Such a computational scheme allows us to reach more accurate fits than those obtained by Shapiro et al. (2007a) and improve our understanding of the scattering polarization in the CN violet system. A first analysis will be given in a forthcoming paper.

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