

## Hanle Effect Diagnostics of the Coronal Magnetic Field: A Test Using Realistic Magnetic Field Configurations

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**Abstract.** Our understanding of coronal phenomena, such as coronal plasma thermodynamics, faces a major handicap caused by missing coronal magnetic field measurements. Several lines in the UV wavelength range present suitable sensitivity to determine the coronal magnetic field via the Hanle effect. The latter is a largely unexplored diagnostic of coronal magnetic fields with a very high potential. Here we study the magnitude of the Hanle-effect signal to be expected outside the solar limb due to the Hanle effect in polarized radiation from the H I Ly $\alpha$  and  $\beta$  lines, which are among the brightest lines in the off-limb coronal FUV spectrum. For this purpose we use a magnetic field structure obtained by extrapolating the magnetic field starting from photospheric magnetograms. The diagnostic potential of these lines for determining the coronal magnetic field, as well as their limitations are studied. We show that these lines, in particular H I Ly $\beta$ , are useful for such measurements.

### 1. Introduction

The magnetic field is the main driver of all physical phenomena in the solar corona. The field lines of force thread the solar atmosphere coupling its different layers to the solar interior. They transport energy to the corona, where it is dissipated and heats the plasma to several MK as well as accelerating particles to several hundreds of km s<sup>-1</sup> within a few solar radii above the surface. The magnetic field also affects the interplanetary medium through the transfer of angular momentum from the Sun through the solar wind and transient events. The latter also have important consequences on planets such as the Earth. In spite of its key role, the magnetic field remains an almost unknown parameter for any study involving the solar upper atmosphere.

Measuring the magnetic field vector is a routine exercise in the photosphere and to a smaller degree in the chromosphere. Magnetic fields in these two layers are strong enough to yield an easily measurable Zeeman signal (and also Hanle effect for numerous spectral lines). Inversion techniques of the observed Stokes parameters are sufficiently sophisticated from both, a physical and computational point of view. However, the coronal magnetic field is rather weak, so that the Zeeman splitting in (generally weak) coronal lines is too small to be accurately measured except above active regions with relatively strong field for few spectral lines with exceptionally large Landé factors (Lin, Kuhn, & Coulter 2004). Significant Zeeman splitting is usually accompanied by the so-called “strong regime of the Hanle effect” where the direction of the magnetic field projected on the plane of the sky can be obtained from the linear polarization

signal of spectral lines such as the Fe XIV 530.3 nm green line. However, the coronal plasma is optically thin and direct coronal magnetic field measurements have a line-of-sight integrated character. To obtain the 3D structure of the magnetic field, vector tomographic methods are required (see Kramar, Inhester, & Solanki 2006 and Kramar & Inhester 2007).

Techniques based on different physical mechanisms, such as radio gyroresonant and bremsstrahlung emission, are being developed. However, they provide field strengths in different layers (depending on the frequency-opacity relation) without height information on where the signal comes from (see Lee et al. 1997). They also remain restricted to areas above active regions. These measurements are, however, important to constrain coronal magnetic fields obtained through the extrapolation of photospheric and chromospheric field measurements. Extrapolation techniques of magnetic fields have undergone a rapid development and could benefit enormously from high quality and spatially extended measurements of magnetic fields in the photosphere and chromosphere and probably the lower corona (Solanki et al. 2003).

Theoretically, direct determination of the magnetic field in the solar corona could be achieved through linear polarization of spectral lines with suitable sensitivity to the Hanle effect. Raouafi et al. (1999a,b) successfully measured the linear polarization of the O VI 103.2 nm line and interpreted it in terms of the Hanle effect signature of the coronal magnetic field (see also Raouafi et al. 2002a,b).

The aim of the present paper is to study the possibility of measuring the coronal magnetic field vector through the Hanle effect using coronal lines with both, relatively adequate sensitivity to the field and high emissivity. The study aims to be relatively realistic in the sense that the magnetic field used is an extrapolation of photospheric measurements. The results presented here are in a preliminary stage and the different inputs to the method have to be improved in the future in order to be used to underpin future missions to measure the coronal magnetic field directly.

## 2. Hanle Effect

The Hanle effect is the result of interferences between different sub-levels of a given atomic transition. This occurs in resonant scattering conditions when the magnetic field and the upper (or lower) level of the transition fulfill the following relation

$$\frac{g_J \mu_B}{\hbar} \tau B = 1, \quad (1)$$

where  $B$  is the magnetic field strength,  $\tau$  is the lifetime of the atomic level,  $g_J$  its Landé factor,  $\mu_B$  is the Bohr magneton and  $\hbar$  the reduced Planck's constant.

In the solar corona ( $B < 100$  Gauss), the Hanle effect works better in the ultraviolet and extreme ultraviolet wavelength ranges (see Table 1). The effect on the linear polarization depends on both the magnitude and direction of the magnetic field vector. An advantage with respect to the Zeeman effect is that the spectral resolution is not a critical requirement since the linear polarization resulting from resonant scattering is of one sign.

Table 1. Sensitivity to the Hanle effect of H I and O VI 103.2 nm lines

Line	$\lambda$ ( $\text{\AA}$ )	$A_{ul}$ ( $10^8 \text{ s}^{-1}$ )	$B_{\text{Hanle}}$ (Gauss)
H I Ly- $\alpha$	1215.16	6.265	53.43
H I Ly- $\beta$	1025.72	1.672	14.26
H I Ly- $\gamma$	972.53	0.682	5.81
H I Ly- $\delta$	949.74	0.344	2.93
O VI	1031.91	4.160	35.48

### 3. Polarization in H I Lines

H I Ly $\alpha$  and Ly $\beta$  are both formed by doublets at practically the same wavelength each (1215.668  $\text{\AA}$   $1s^2S_{1/2} - 2p^2P_{3/2}$  and 1215.674  $\text{\AA}$   $1s^2S_{1/2} - 2p^2P_{1/2}$  for Ly $\alpha$  and 1025.722  $\text{\AA}$   $1s^2S_{1/2} - 3p^2P_{3/2}$  and 1025.723  $\text{\AA}$   $1s^2S_{1/2} - 3p^2P_{1/2}$  for Ly $\beta$ ). Lifetimes of the components of each doublet are the same (see Table 1) and the first components can be linearly polarized in resonant scattering conditions. The second components are not polarizable. These two lines are the most intense lines emitted in the solar corona, where Ly $\alpha$  is almost exclusively formed by resonant scattering of the chromospheric radiation (the collisional component contributes less than 1%). Ly $\beta$  has an important contribution from electron collisions which usually diminishes the degree of linear polarization of the line. It does not, however, affect the direction of the plane of polarization.

### 4. Model for the Solar Corona

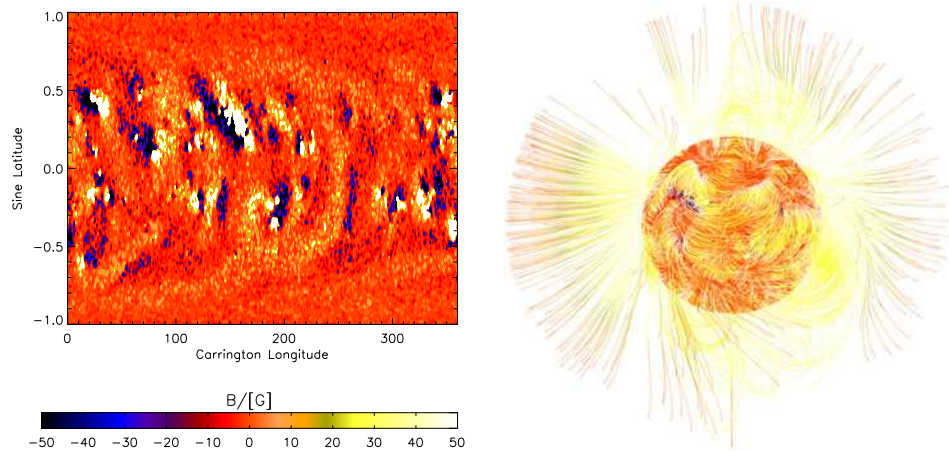


Figure 1. *Left:* Synoptic map of the photospheric magnetic field from SOHO/MDI for Carrington rotation 1975. *Right:* Coronal field topology obtained from potential field extrapolation.

As a first step towards a realistic coronal magnetic field model, we consider a coronal magnetic field distribution obtained from potential field extrapolation

of photospheric measurements from SOHO/MDI. We choose the synoptic map for Carrington rotation number 1975, which corresponds to maximum activity of solar cycle 23 (see left panel of Figure 1). The grid resolution in spherical coordinates is  $40 \times 80 \times 160$  in  $r$ ,  $\theta$  and  $\varphi$  ( $1 R_{\odot} \leq r \leq 2.5 R_{\odot}$ , with a step of  $0.0375 R_{\odot}$ ,  $0^{\circ} \leq \theta \leq 180^{\circ}$  with a step of  $2.5^{\circ}$ ,  $0^{\circ} \leq \varphi \leq 360^{\circ}$  with a step of  $2.5^{\circ}$ ). Spherical harmonics up to  $l = 20$  have been used for computing the coronal magnetic field. The right panel of the same Figure illustrates the topology of the field lines of force.

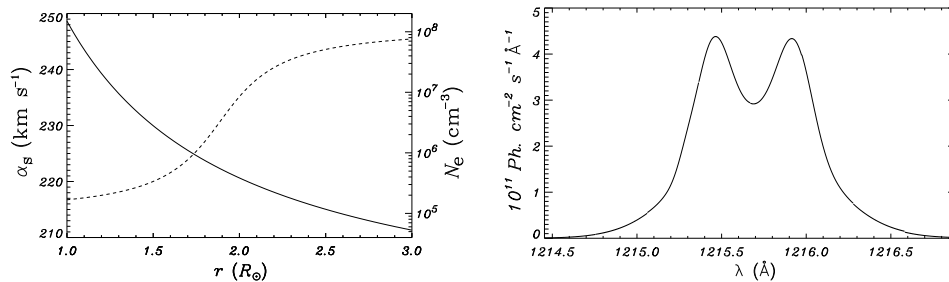


Figure 2. *Left:* Coronal electron density (solid) and velocity turbulence of the hydrogen atoms (dashes) as a function of the distance to Sun center. *Right:* Chromospheric Ly $\alpha$  profile obtained from SOHO/SUMER (see Lemaire et al. 1998).

The electron density model used is from SOHO measurements (left panel of Figure 2; see Doyle et al. 1999). We assume that coronal electron density depends only on the distance to Sun center. This assumption might be appropriate for coronal background densities but not for structures such as loops. To address this problem, a detailed independent study has to be done, which goes beyond the present exploratory study. The coronal plasma is assumed to be in a static state. This holds adequately at low coronal altitudes in particular outside of polar coronal holes due to the low speed of the solar wind and also the large widths of the H I chromospheric lines. The temperature of the plasma is assumed to be isotropic and the velocity turbulence is given by the left panel of Figure 2 (see Raouafi, Harvey, & Solanki 2007). Integration along the line of sight is taken into account. We also assume that coronal atoms are excited exclusively by radiation from the solar disk (see right panel of Figure 2; Lemaire et al. 1998). This is well fulfilled by the case of Ly $\alpha$  but not of Ly $\beta$  which has an important collisional component. However, we are primarily interested in the direction of the plane of polarization that is defined only by Stokes parameters  $Q$  and  $U$ , which are created only by radiative excitations.

## 5. Results and Discussion

Figure 3 displays the direction of the plane of polarization with respect to the tangent to the solar limb for H I Ly $\alpha$  (left) and Ly $\beta$  (right). The angle of rotation of the plane of polarization is represented by the grey scales plotted below each panel.

Although these results are still preliminary, they suggest that the hydrogen Ly $\alpha$  and  $\beta$  lines could be very useful for measuring the coronal magnetic field. Theoretical polarization rates (not shown here) in these coronal lines are reasonably high and then could be easily gauged. However, despite the fact that the extrapolation has a significant periodic effect on the outcome of the calculations, it is also clear that large values of the rotation angle of the polarization direction have often spatial coherence with concentrations of magnetic field lines as shown by the top-right panel of Figure 1. Generally, the obtained values are well within the measurement capability of actual polarimeters (say  $1^\circ$ ). This is encouraging indeed, although numerous aspects in the model could be improved significantly. The present study reveals also the limits of field extrapolation techniques when a limited number of orders in the solution are considered. The latter might be sufficient to approximate the field topology to the Extreme UltraViolet (EUV) coronal structure, but not for quantitative studies such as the present one.

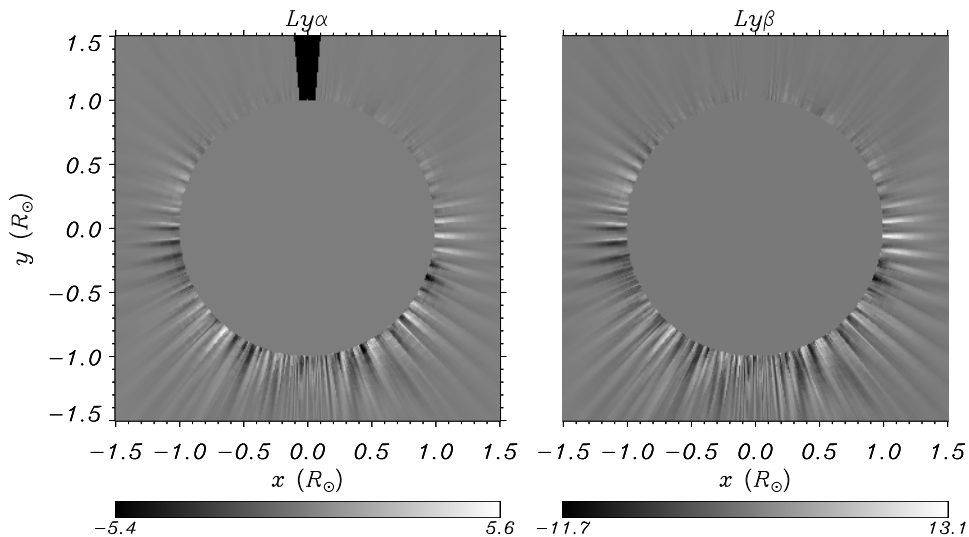


Figure 3. Plane of polarization direction with respect to the tangent to the solar limb for H I Ly $\alpha$  (left) and  $\beta$  (right) obtained from Hanle effect due the magnetic field data and the coronal parameters presented in the previous section. Integration along the line of sight is taken into account. The grey scales at the bottom indicate the angle of rotation of the polarization direction rotation in degrees. The regular (periodic) azimuthal structure is due to the limited orders of spherical harmonics (20 first orders) used in the extrapolation of the photospheric field. However, significant values of the rotation angle of the plane of polarization coincide with flux concentrations as shown in Figure 1, which reflect the Hanle effect due the magnetic field.

The main problem facing off-limb observations is that such measurements integrate along the line of sight over structures with different magnetic field strengths and geometries. Even though the region exactly above the limb (at quadrature) will have the greatest weight, this integration makes the interpretation difficult.

## 6. Conclusion

Although the model used to compute the polarization of the hydrogen lines is very simple and can be significantly improved in numerous aspects, significant and practically measurable polarization parameters (rates and direction angles of the plane of polarization) due to the Hanle effect resulting from the coronal magnetic field are obtained. The use of coronal magnetic field data obtained from the potential field extrapolation of photospheric magnetograms is a step forward in realistically modeling solar coronal magnetic phenomena. Future missions will benefit from such simulations of the measurement of the coronal magnetic field.

Hanle effect measurements in the UV are a promising way of measuring the Sun's coronal magnetic field, although due to the lack of appropriate instruments the use of the technique has so far been limited (e.g. Raouafi et al. 1999a,b).  $\text{Ly}\alpha$  and  $\beta$  are promising spectral lines for coronal Hanle effect measurements. Their Hanle sensitivity to different field strengths and their different formation processes make them complementary to each other. The polarization of several other spectral lines (e.g., O VI 1032 Å) have to be explored in order to widen the choice range for any attempt to measure the magnetic field in the solar corona.

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