SOLAR CORONAL MAGNETIC FIELD MAPPER

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ABSTRACT

The relative lack of knowledge of the coronal vector magnetic field is a major handicap for progress in coronal physics. The Hanle effect in UV spectral lines is a largely unexplored diagnostic of coronal magnetic fields with a very high potential. Here we study the magnitude of the signal to be expected for typical coronal fields for the particular example of the hydrogen Lyman α line and show that this line may be useful for such measurements, in particular in combination with a disk imager. We propose that an EUV coronal magnetic field mapper should be a central part of the science payload of any future space-based solar observatory.

Key words: Sun, Corona, Magnetic field.

1. INTRODUCTION

The solar magnetic field dominates the energetics and dynamics of the transition region and coronal plasma, but is relatively poorly known at these heights. Methods of measuring the field are best developed for the photosphere (using the Zeeman effect and more recently the Hanle effect). The extrapolation of magnetic fields starting from photospheric measurements sets important constraints on coronal magnetic structure. However, this technique faces some hurdles: 1. Accuracy in the measurements of the photospheric fields is an important ingredient for any field extrapolation to the corona. 2. The measured photospheric vector field suffers from a $180°$ ambiguity in its azimuth, which can result in incorrect extrapolations. 3. The usual assumption underlying the extrapolations is that the magnetic field is force free in the photosphere, which is not fulfilled. 4. Realistic extrapolations involving non-linear force-free fields are computationally very expensive.

The alternative to extrapolations from the photosphere is to measure the field in the corona. Various techniques have been applied to achieve this aim. The most common technique has been to measure the magnetic field using gyroresonant emission in the radio spectral range. This technique is mainly limited to strong fields (field strength $B > 250$ Gauss; White 2005). Another diagnostic available to radio telescopes is bremsstrahlung emission. Circular polarization measurements allow the longitudinal component of even relatively weak magnetic fields to be measured (see Gelfreikh 2004). A more indirect method of obtaining the field strength B of (groups of) loops is from the analysis of their oscillations seen by, e.g., EUV imagers and spectrographs (Nakariakov & Ofman 2001). Spectropolarimetric coronagraphy in the so-called Hanle strong field regime allows an estimate of the magnetic field direction in the plane of the sky from scattering polarization measurements (Charvin 1965) and more recently the measurement of the longitudinal magnetic field from Zeeman split coronal spectral lines (Harvey 1969 and more recently Lin et al. 2000 & 2004).

A new and so far rarely applied technique is to measure the coronal field via the Hanle effect in EUV resonance lines by determining the linear polarization in the EUV. Raouafi (2000, 2002) and Raouafi et al. (2002) successfully measured the magnetic field above a polar coronal hole with this technique. In this contribution we consider this approach and discuss it using the example of the Ly α line. It has the advantage of being the strongest line in the solar EUV spectrum and thus providing a good signal-to-noise ratio. We present computations that test whether a measurable Hanle signature in this line can be determined. Earlier important work on this topic has been published by Bommier and Sahal-Bréchot (1982) and by Fineschi et al. (1991).

2. HANLE EFFECT

The Hanle effect is a quantum interference effect occuring when the splitting between atomic levels caused by the magnetic field is of the same order as the natural damping width of the spectral line (e.g. Stenflo 1994). The phenomenology is relatively simple: Resonant scattering produces a significant linear polarization in appropriate spectral lines near or above the solar limb (generally the polarization is directed parallel to the solar limb). Through the Hanle effect, the magnetic field changes the magnitude and the direction of the linear polarization. In principle the Hanle effect provides information which can be used to derive the full magnetic vector. The sensitivity

Proc. SOHO 17 – 10 Years of SOHO and Beyond, Giardini Naxos, Sicily, Italy
7 – 12 May 2006 (ESA SP-617, July 2006)

of a spectral line to the magnetic field depends on: 1. the field strength relative to the critical field strength of the line; 2. the level of resonant polarization in the line relative to the noise level; 3. the direction of the field (or the distribution of directions, if the magnetic structure is not resolved by the observations).

For Ly α the critical field strength is ≈ 71 Gauss. The line is relatively insensitive to field strengths that are much (e.g. > 5 times) smaller or much (e.g. > 5 times) larger than this value.

The measurement of the magnetic field via the Hanle effect requires a polarimeter combined with a spectrometer or a narrow-band imager or a narrow-band coronagraph. In general, resonant scattering produces only a single sign of polarized light, so that the spectral line does not need to be spectrally resolved (as is the case for the Zeeman effect).

3. COMPUTATIONS AND RESULTS

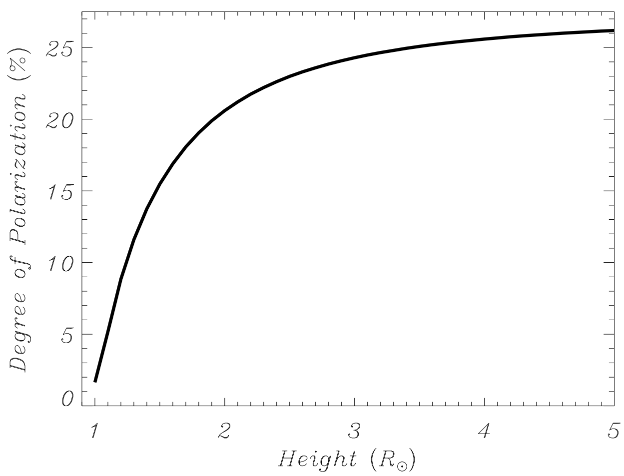

Figure 1. Degree of polarization shown by Ly α in the absence of a magnetic field vs. distance from solar disk centre, starting just above the limb.

We have computed Ly α line polarization in simple homogeneous atmospheres both off-limb and on-disk. The basic assumptions of the computations are: 1. The line is optically thin. This is well achieved sufficiently far off the limb, but may have to be reconsidered on the disk. 2. There is no limb brightening or darkening. This is roughly fulfilled by Ly α (Bonnet et al. 1980). Note that this assumption is conservative in the sense that any limb brightening or darkening will give rise to a larger scattering polarization level. 3. We carry out no integration along the LOS. This is mainly of importance for the off-limb computations. 4. The radiation from below exciting the transition has a Gaussian profile shape with a Doppler width of 150 km/s. 5. Only the scattered fraction of the radiation is considered (this is no problem off limb, where this assumption is well-satisfied, but will have to be considered more carefully on disk). 6. The scattering atoms suffer a turbulent broadening of 200 km/s, a value that is in good agreement with the UVCS Ly α data. 7. Solar wind and other bulk motions are neglected. This is of relevance mainly for the off-limb computations.

Under these assumptions we obtain the following results. Figure 1 shows the relative amount of resonance polarization expected to be produced in the Ly α line. The polarization asymptotically reaches a maximum value of 27% sufficiently far from the solar surface (see Beckers 1974; Bommier and Sahal-Bréchot 1982). Interestingly, it does not drop below 1.8%, even at the solar surface. This indicates that if a sufficiently high S/N can be achieved, observations of the field will be possible also on the disk.

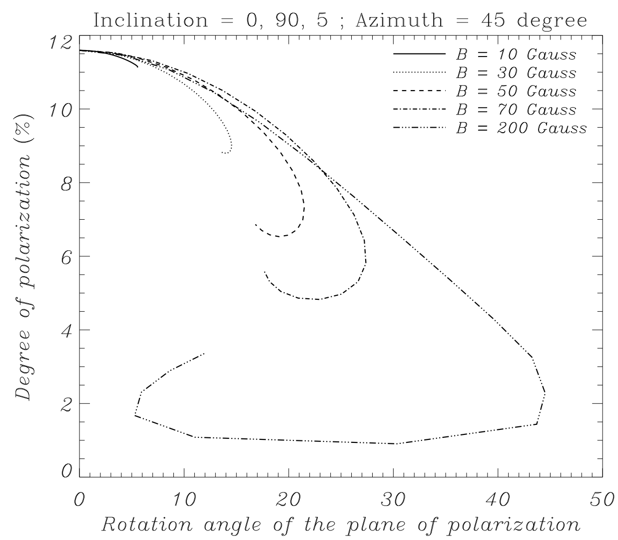

Figure 2. Off-limb signature of Magnetic field in Ly α (degree of polarization vs. the unsigned rotation angle of the linear polarization) for 1.3$R_\odot$ from solar disk centre. Inclination angle = 0 at the leftmost point of each curve, increasing to $90°$ at the other end.

In Figure 2 we plot the influence of the Hanle effect on the Ly α linear polarization at one particular height above the solar limb (0.3 $R_\odot$). Each curve refers to a given field strength. For a field-free gas the polarization is unchanged relative to the scattering polarization (i.e. rotation angle $= 0°$). The field strength is represented by the line style (see upper right of the figure). For each field strength, computations are carried out for inclinations of the magnetic vector to the line of sight ranging from 0 to $90°$ in steps of $5°$, giving the different points along a line belonging to a fixed field strength. The azimuth of the field vector with respect to the tangent to the solar limb is kept fixed at $45°$ in all computations. For weak fields of 10 Gauss, the polarization rotates by a small amount (corresponding to the short solid line) and hardly decreases. As the strength of the field increases, so does its influence on the Ly α polarization. The diagnostic capabilities of the line are best when for a set of parameters, the polarization occupies a unique corner of the diagram. As can be seen from the figure, there is a partial overlap between most of the lines. For example, it is not possible to distinguish between different field strengths at small inclination angles. At large inclinations and $B \geq 30$ Gauss the curves do not overlap and the magnetic vector can in principle be uniquely determined. At $B = 200$ Gauss, the depolarization of the line is very large for almost all inclination angles. It therefore becomes difficult to distinguish this field strength from even higher ones using the Hanle effect.

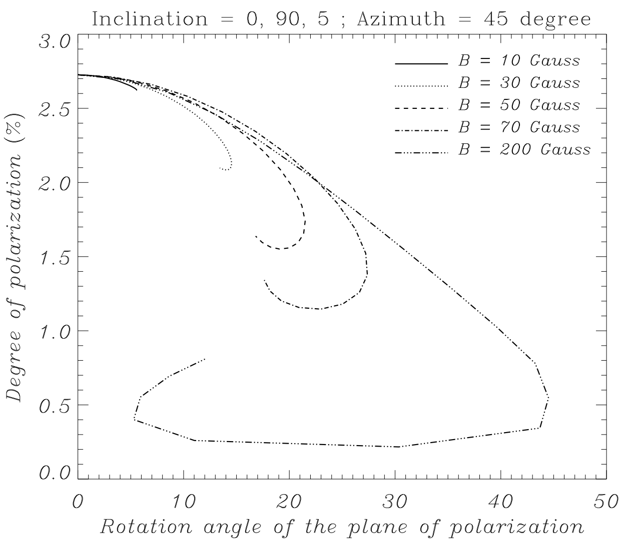

Figure 3. The same as Figure 2, but for $1.05\ R_\odot$ *from solar disk centre.*

Figure 3 is very similar to Figure 2, except that it refers to a location much closer to the solar limb. The difference between these two figures is basically that the resonant polarization level is significantly lower, 2.7% instead of 11.6% at $1.3\ R_\odot$. This implies that the polarization measured for a 200 Gauss field at $1.05\ R_\odot$ drops to around 0.3%. On the other hand, the total brightness of Ly α is much larger by 1-2 orders of magnitude at $1.05\ R_\odot$ than at $1.3\ R_\odot$. Thus, the signal remains sufficiently high to measure low polarization.

Finally, in Figure 4 we consider the case of observations carried out on the solar disk. The three panels refer, from top to bottom, to $\mu = \cos\theta = 0.65, 0.35$ and 0.2, respectively. A single field strength, $B = 70$ Gauss, was used throughout the computations made for this figure. This B value is very close to the Ly α critical field strength. The different lines in each frame now refer to different azimuths of the magnetic vector: 0° (dashed), 45° (dotted) and 90° (solid). The computations were carried out for inclination angles between 0 and 90°, in steps of 5°, each of which gives a point along a given line. It follows from this figure that measurements over roughly the outer third of the disk should be possible if sufficiently high S/N observations are carried out.

4. DISCUSSION

Although these results are still preliminary, they suggest that the hydrogen Ly α line may be quite useful for measuring the coronal magnetic field using the Hanle effect. Due to the relatively large critical field strength of 71 Gauss, Ly α should be most useful relatively close to the solar surface or in strong active regions, where the field strength is relatively large. This means that a disk imager is to be preferred over a coronagraph for this particular line. However, for other spectral lines, a coronagraph may be more appropriate.

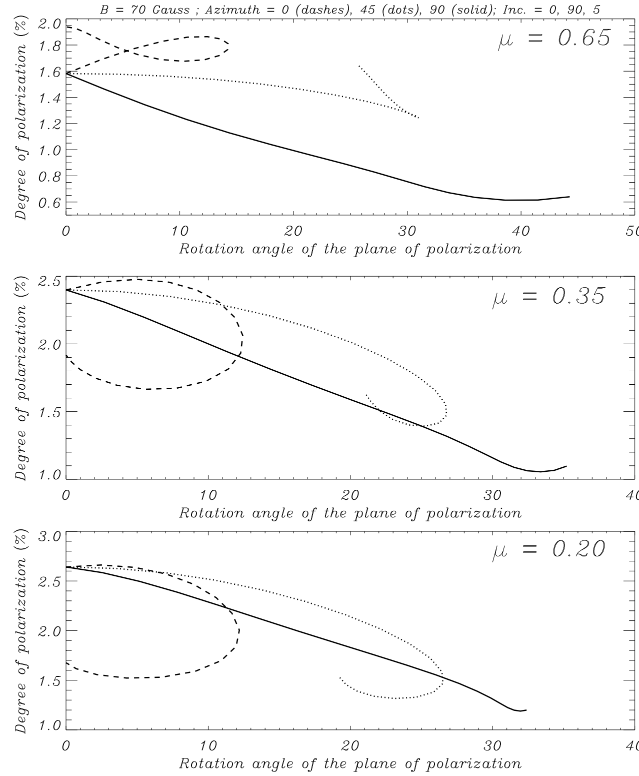

Figure 4. On-disk signature of the Hanle effect in Ly α *for different magnetic vectors.*

In spite of the significant potential of the technique outlined above, it is beset by problems of the reliable physical interpretation of the data. Below we briefly discuss the main problems from which the data interpretation suffers, separately for observations made on-disk and off-limb.

The main problem facing on-disk observations is that the degree of scattering polarization depends strongly on the level of anisotropy of the incident radiation, which in turn depends strongly on the height at which the scattering process takes place. From the Hanle effect alone it is impossible to determine this height and images made on disk often do not allow this height to be unambiguously determined. As a solution we propose to combine the Hanle measurement with extrapolations of the field starting from photospheric magnetograms. This means, however, that observations will have to be made sufficiently far from the limb to allow accurate extrapolations to be carried out. The SOLIS magnetograph and the HMI instrument on SDO will provide excellent data of this type.

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. The solution we propose is to make use of vector tomography to disentangle such line-of-sight integration effects. A method to apply vector tomography techniques to solar data have been worked out by Kramar et al. (2006). Of course, such a technique requires regular observations over multiple days and is restricted to slowly changing features (unless stereoscopic observations are possible).

5. CONCLUSIONS

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 2000 & 2002 and Raouafi et al. 2002). We propose that a coronal magnetic field mapper is an important instrument which should be seriously considered to be a part of the payload on the next generation solar space mission, in particular of an observatory type mission. Ly α is a promising spectral line for chromospheric and coronal Hanle effect measurements. Since it is sensitive to relatively strong fields of $B \approx 70$ Gauss, it is better suited for on-disk observing. The principle problems facing an interpretation of EUV Hanle data can be overcome with modern techniques. The Max Planck Institute for Solar System Research has proposed to add such a capability to the EUV imager on the Kuafu mission.

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