Two Suggestions to See the Hidden Magnetism of the Solar Chromosphere

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Abstract. Solar magnetic fields leave their fingerprints in the polarization signatures of the emergent spectral line radiation. This occurs through a variety of rather unfamiliar physical mechanisms, not only via the Zeeman effect. In particular, magnetic fields modify the atomic level polarization (population imbalances and quantum coherences) that anisotropic radiative pumping processes induce in the atoms and molecules of the solar atmosphere. Interestingly, this so-called Hanle effect allows us to “see” magnetic fields to which the Zeeman effect is blind within the limitations of the available instrumentation. Here I argue that the Ca ii IR triplet and the He i 10830 Å multiplet would be very suitable choices for investigating the magnetism of the solar chromosphere via spectropolarimetric observations from a future space telescope, such as JAXA’s SOLAR-C mission.

1. Introduction

We may define “the Sun’s hidden magnetism” as all the magnetic fields of the extended solar atmosphere that are impossible to diagnose via the only consideration of the Zeeman effect. Contrary to what one might think, there are many examples that belong to this category:

- Most of the magnetism of the quiet solar photosphere.
- The magnetic fields of the solar chromosphere outside sunspots, including the spike-like jet features that we call spicules.
- The magnetic fields that confine the plasma of solar prominences and filaments, including those of active regions.
- The magnetism of the solar transition region and corona.

The reasons are the following, but see more information in the paper by Trujillo Bueno (2009) on Recent Advances in Chromospheric and Coronal Polarization Diagnostics. First, the polarization of the Zeeman effect as a diagnostic tool is blind to magnetic fields that are randomly oriented on scales too small to be resolved. Second, the circular polarization induced by the longitudinal Zeeman effect scales with the ratio, $R$, between the Zeeman splitting and the Doppler broadened line width, while the Stokes $Q$ and $U$ signals produced by the transverse Zeeman effect scale as $R^2$. Therefore, the Zeeman effect is of limited practical interest for the exploration of magnetic fields in hot (chromospheric and coronal) plasmas.
Fortunately, there is another physical mechanism by means of which the magnetic fields of the solar atmosphere leave fingerprints in the polarization of the emergent spectral line radiation: the Hanle effect. Anisotropic radiation pumping processes produce atomic level polarization (i.e., population imbalances and quantum coherences among the magnetic sublevels pertaining to any given degenerate energy level). The Hanle effect can be defined as any modification of the atomic level polarization due to the presence of a magnetic field, including the remarkable effects produced by the level crossings and repulsions that take place when going from the Zeeman effect regime to the complete Paschen-Back effect regime (e.g., Landi Degl’Innocenti & Landolfi 2004). The Hanle effect is especially sensitive to magnetic strengths between $0.1 \, B_H$ and $10 \, B_H$, where the critical Hanle field intensity ($B_H$, in gauss) is that for which the Zeeman splitting of the $J$-level under consideration is similar to its natural width: $B_H = (1.137 \times 10^{-7})/(t_{\text{life}} \, g_J)$ (with $g_J$ the level’s Landé factor and $t_{\text{life}}$ its radiative lifetime in seconds). Since the lifetimes of the upper levels ($J_u$) of the transitions of interest are usually much smaller than those of the lower levels ($J_l$), clearly diagnostic techniques based on the lower-level Hanle effect are sensitive to much weaker fields than those based on the upper-level Hanle effect. Summarizing:

- The Hanle effect is sensitive to weaker magnetic fields than the Zeeman effect: from at least 1 mG to a few hundred gauss. Moreover, it is sensitive to magnetic fields that are randomly oriented on scales too small to be resolved (e.g., the Hanle-effect investigation by Trujillo Bueno et al. (2004) showed that the bulk of the “quiet” photosphere is teeming with tangled magnetic fields at subresolution scales, with $\langle B \rangle \sim 100$ G, which support the suggestion that a solar surface dynamo plays a significant role for the quiet Sun magnetism).

- The Hanle effect as a diagnostic tool is not limited to a narrow solar limb zone. In particular, in the forward scattering geometry of a solar disk center observation, the Hanle effect creates linear polarization in the presence of an inclined magnetic field (e.g., Trujillo Bueno et al. 2002).

The disadvantage of the Hanle effect as a diagnostic tool is that for magnetic strengths $B > 10 \, B_H(J_u)$ the linear polarization signals are sensitive only to the orientation of the magnetic field vector. Fortunately, the Hanle and Zeeman effects can be suitably complemented for exploring magnetic fields in solar and stellar physics.

2. How to explore the magnetic fields of the solar chromosphere?

There are several possibilities for mapping the magnetic fields of the solar chromosphere, but the following spectral lines would be very suitable choices to guarantee important scientific discoveries via spectropolarimetric observations from a future space telescope, like JAXA’s SOLAR-C mission.

2.1. The IR triplet of Ca II

We already know that diagnostic techniques based on the Zeeman effect in the Ca II IR triplet are very useful for obtaining information on the three-dimensional
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Figure 1. An example of our recent spectropolarimetric observations of the Ca II 8542 Å line in a very quiet region close to the solar limb, using ZIMPOL at the French-Italian telescope THEMIS. The reference direction for Stokes Q is the tangent to the closest limb. From Trujillo Bueno et al. (2009).

structure of sunspots magnetic fields (e.g., Socas-Navarro et al. 2000; Socas-Navarro 2005). But, what Stokes profiles do we see outside sunspots?

Figure 1 shows a high-sensitivity spectropolarimetric observation of the quiet solar chromosphere in the strongest (8542 Å) line of the Ca II triplet. It was obtained by R. Ramelli (IRSOL), R. Manso Sainz (IAC) and me using the Zürich Imaging Polarimeter (ZIMPOL) attached to THEMIS. The observed Stokes V/I profiles are clearly caused by the longitudinal Zeeman effect, but the Stokes Q/I and U/I signals are produced mainly by the influence of atomic level polarization. Although the spatio-temporal resolution of this spectropolarimetric observation is rather low (i.e., no better than 3″ and 20 minutes), the fractional polarization amplitudes fluctuate between 0.01% and 0.1% along the spatial direction of the spectrograph’s slit, with a typical spatial scale of 5″. Note that while the Stokes Q/I signal changes its amplitude but remains always positive along that spatial direction, the sign of the Stokes U/I signal fluctuates.

The physical interpretation of these spectropolarimetric observations requires solving the so-called NLTE problem of the 2nd kind (e.g., via the application of the multilevel radiative transfer code MULTIPOL described in Manso Sainz & Trujillo Bueno 2003a). Interestingly, while the scattering polarization in the 8498 Å line shows sensitivity to inclined magnetic fields with strengths between 1 mG and 50 G, the emergent linear polarization in the 8542 Å and 8662 Å lines is sensitive to magnetic fields in the milligauss range (Manso Sainz & Trujillo Bueno 2007). The reason for this very interesting behavior is that the scattering polarization in the 8498 Å line gets a significant contribution from the selective emission processes that result from the atomic polarization of the short-lived upper level, while that in the 8542 Å and 8662 Å lines is dominated by the selective absorption processes that result from the atomic polarization of the metastable (long-lived) lower levels (Manso Sainz & Trujillo Bueno 2003b). Therefore, in “quiet” regions of a stellar atmosphere the magnetic sensitivity of the linear polarization of the 8542 Å and 8662 Å lines is controlled by the lower-level Hanle effect, which implies that in regions with $1 \lesssim B \lesssim 50$ G the Stokes Q and U profiles are only sensitive to the orientation of the magnetic field vector. In such regions the 8498 Å line is however sensitive to both the orientation and the strength of the magnetic field through the upper-level Hanle effect. As expected, our multilevel radiative transfer calculations for the interpretation of the observations of Fig. 1 show that the spatial variations in the observed frac-
Figure 2. He \textsc{i} 10830 Å spectropolarimetric observation of polar faculae obtained in collaboration with M. Collados (IAC) using the Tenerife Infrared Polarimeter attached to the German Vacuum Tower Telescope.

Tional linear polarization are mainly due to changes in the orientation of the chromospheric magnetic field.

These types of polarization signal resulting from atomic level polarization and the Hanle and Zeeman effects can be exploited to explore the thermal and magnetic structure of the solar chromosphere. They can also be used to evaluate the degree of realism of magneto-hydrodynamic simulations of the photosphere-chromosphere system via careful comparisons of the observed Stokes profiles with those obtained through forward-modeling.

2.2. The He \textsc{i} 10830 Å multiplet

A very suitable diagnostic window for inferring the magnetic field vector of plasma structures embedded in the solar chromosphere and corona is that provided by the polarization produced by the joint action of atomic level polarization and the Hanle and Zeeman effects in the He \textsc{i} 10830 Å triplet. Off-limb observations give information on the magnetic field of spicules and prominences (e.g., Trujillo Bueno et al. 2005; Merenda et al. 2006) while on-disk observations show amazing polarization signatures in a variety of plasma structures, such as filaments in quiet and active regions (e.g., Trujillo Bueno et al. 2002; Kuckein et al. 2009), emerging flux regions (e.g., Solanki et al. 2003), sunspots (e.g., Centeno et al. 2006), flaring regions (e.g., Sasso et al. 2007), etc. The order of magnitude of the ensuing polarization amplitudes varies between 0.1% and 1%, approximately, while they are $\sim 0.01\%$ in quiet regions at the solar disk center (see Asensio Ramos et al. 2008). Moreover, Fig. 2 shows a very interesting example of the Stokes profiles observed in polar faculae. The fact that there is a nearby photospheric line of Si \textsc{i} whose polarization is caused by the Zeeman effect, makes the 10830 Å spectral region very suitable for investigating the coupling between the photosphere and the corona. For field strengths $B \lesssim 100$ G the linear polarization of the He \textsc{i} 10830 Å triplet is fully dominated by the atomic level polarization that is produced by anisotropic radiation pumping processes
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(Trujillo Bueno et al. 2002). For instance, in Fig. 2 the linear polarization of the He i 10830 Å triplet is mainly caused by atomic level polarization, while the circular polarization is produced by the longitudinal Zeeman effect. For field strengths $100 < B \lesssim 2000$ G the linear polarization of the He i 10830 Å triplet is caused by the joint action of atomic level polarization and the transverse Zeeman effect (Trujillo Bueno & Asensio Ramos 2007). This can be seen also in Fig. 2 of Trujillo Bueno (2009), which shows examples of model calculations for the case of a plasma structure levitating at a height of 2200 km above the visible solar surface and permeated by a magnetic field of 1200 G with different orientations. In particular, that figure emphasizes that the influence of atomic level polarization on the linear polarization of the He i 10830 Å triplet is very significant, even for magnetic fields as strong as 1200 G, and that it removes the $180^\circ$ azimuth ambiguity present in the Zeeman-effect profiles.

| Table 1. The Ca II IR triplet |
|-----------------------------|
| **Pros** | **Cons** |
| Provides information on the thermal and the magnetic structure, all the way up from the photosphere to the bulk of the chromosphere. | Not the ideal choice for studying the magnetic field that confines the plasma of structures embedded in the solar chromosphere and corona. |
| The polarization signals are sensitive to magnetic fields from mG to kG strengths. | The forward scattering polarization signals are very weak, but nevertheless measurable through longer integration times. |
| Good choice to evaluate the reliability of MHD models of the photosphere and chromosphere via spectral synthesis and comparison with observations. | Stokes inversion of the magnetic field is possible, but requires a model for the thermal and density stratification. |

| Table 2. The He i 10830 Å triplet |
|-----------------------------|
| **Pros** | **Cons** |
| Good choice for studying the magnetic field that confines the plasma of structures embedded in the solar chromosphere and corona. | Not a very suitable choice to study the magnetism of the quiet chromosphere (see, however, §3.3 and §5.4 in Asensio Ramos et al. 2008). |
| Photospheric lines are present in the same spectral region, so information on photospheric magnetic fields can also be obtained. | It is difficult to obtain information on the thermal and/or density structure. |
| Stokes inversion of the magnetic field vector is possible (e.g., via the Hanle+Zeeman code HAZEL developed by Asensio Ramos et al. 2008). | Not suitable to evaluate the reliability of MHD models of the solar photosphere and chromosphere. |
3. Concluding comments

The exposure time needed for detecting 0.1% (0.01%) fractional polarization signals with a spectral resolution of 50 m\AA and a spatial resolution of 1" in any of the considered triplets is of the order of 1 s (60 s), assuming a 1m aperture telescope having an overall throughput of 10%. Tables 1 and 2 summarize the advantages and disadvantages of the information provided by the Stokes profiles produced by atomic level polarization and the Hanle and Zeeman effects in both triplets. While the Ca II IR triplet is very suitable for exploring the thermal and magnetic structure of the bulk of the solar chromosphere, the He I 10830 Å triplet is the best choice for determining the magnetic field of plasma structures embedded in the solar chromosphere and corona. Obviously, it would be ideal to develop high-sensitivity polarimeters to observe both triplets from a space telescope, but choosing only one of them would already allow us to discover hitherto unknown aspects of the Sun’s hidden magnetism.

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