On the Sensitivity of the Hα Scattering Polarization to Chromospheric Magnetism

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Abstract. A particularly interesting line for exploring the physical conditions of the quiet solar chromosphere is Hα, but its intensity profile is magnetically insensitive and the small circular polarization signatures produced by the longitudinal Zeeman effect come mainly from the underlying photosphere. Here we show that the Hanle effect in Hα provides quantitative information on the magnetism of the quiet chromosphere. To this end, we calculate the response function of the emergent scattering polarization to perturbations in the magnetic field.

Key words. magnetic fields – polarization – radiative transfer – scattering – Sun: chromosphere

1. Introduction

The only way to obtain reliable empirical information on the magnetic fields of the solar chromosphere is through the measurement and physical interpretation of the emergent polarization in chromospheric spectral lines. A particularly important line is Hα, because high-spatial resolution intensity images taken at its very line center reveal the fine scale structuring of the quiet solar chromosphere. Unfortunately, the Hα line is so broad that in the quiet chromosphere the Zeeman effect is of little practical interest (see below). Fortunately, there is a less familiar physical mechanism that produces linear polarization in the Hα line: scattering polarization and its modification by the Hanle effect. Here we show that the scattering polarization in Hα provides quantitative information on the magnetic structure of the upper quiet chromosphere.

2. Scattering polarization in Hα

Hα in the quiet solar chromosphere is a strong absorption line which is formed under highly non-local conditions. It is a septuplet resulting from seven allowed transitions between the fine structure levels of the n = 2 and n = 3 levels. The atomic terms and the fine structure levels pertaining to the same n level are quasi-degenerated. Thus, the individual line compo-

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Fig. 1. The Hα line is composed of 7 fine-structure components, 4 of which (full bars) are responsible of the observed linear polarization. Compare the splitting of the components with the width of the Doppler-broadened intensity profile.

Fig. 2. The observed (Gandorfer 2000) Q/I profile at $\mu = 0.1$ vs. the calculated emergent profile in the non-magnetic atmosphere of Fontenla et al. (1993) hereafter FAL-C model). Positive Q/I corresponds to the tangential direction of polarization. The observed linear polarization profile represents an average profile resulting from sacrificing the spatial and temporal resolution. The disagreement between the two profiles suggests that there is a missing fundamental ingredient in such a model: the magnetic field (see text for details).

The Hα line center is formed in the upper chromosphere while the wings originate in the photosphere (Schoolman 1972). The temperature minimum region is transparent to Hα radiation because the population of the $n = 2$ level is too small there to produce sufficient absorption in Hα. As a result, the response of the line’s Stokes $V$ signal to the Zeeman effect is concentrated mainly in the photosphere of the chosen quiet atmospheric model (Socas-Navarro & Uitenbroek 2004). Another problem with the Zeeman effect in the Hα line is that the field strength required to produce significant Stokes-V signals is too high for the quiet chromosphere. In conclusion, the Zeeman effect in Hα is unsuitable for diagnostics of the quiet chromosphere.

Fortunately, the Hα line observed by Gandorfer (2000) close to the quiet solar limb shows a positive fractional linear polarization $Q/I$ profile with the maximum value at the line center (see Fig. 2). This scattering polarization signal results from the population imbalances and quantum coherences among the magnetic sublevels of the line’s upper levels that are produced by anisotropic optical pumping processes (eg. Trujillo Bueno 2009). While each of the 7 components of the line contributes to the absorption coefficient, only 4 of them (those with total angular momentum of the upper level $J_u > 1/2$) contribute to the emission of polarized photons. The emergent linear polarization is modified by a magnetic field via the so-called Hanle effect, which operates mainly in the line core (eg. Stenflo 1994; Landi Degl’Innocenti 2004). We point out that “zero-field dichroism” in the quiet chromosphere (Trujillo Bueno & Landi Degl’Innocenti 1997; Manso Sainz & Trujillo Bueno 2003) is negligible for Hα so that the $2p_{3/2} - 3s_{1/2}$ transition does not selectively absorb the incident radiation.

The sensitivity of the Hα line polarization to the magnetic field in the quiet chromosphere is investigated here by solving the multilevel non-LTE radiative transfer problem taking into account all the relevant physical processes (anisotropic optical pumping, atomic level polarization, Hanle effect, collisional depolarization, etc.). Fig. 3 shows the line-center values of the calculated $Q/I$ profile for 9 different in-
Fig. 3. Q/I amplitude of Hα for a LOS with μ = 0.1 assuming a uniformly magnetized FAL-C atmosphere. We take into account depolarization by collisions (Sahal-Bréchot et al. 1996) and by a random-azimuth magnetic field with the indicated inclination.

clinations of an unresolved (i.e., with a random azimuth) magnetic field. In these model calculations, the field intensity is uniform within the whole atmosphere. Note that the line polarization is sensitive to field strengths between approximately 1 and 50 G.

3. Response functions

The spatio-temporally averaged observation of Gandorfer (2000) shows that at μ = cos θ ≈ 0.1 (with θ being the heliocentric angle) the amplitude of the Q/I profile is about 0.12% (see Fig. 2). To obtain this Q/I amplitude assuming uniform magnetic field in a one-dimensional model like FAL-C we need a magnetic strength larger than ≈ 15 G and with an inclination higher than 40° (cf. Fig. 3). However, the assumption of a homogenous field is unrealistic and it can only provide a first rough guess about the actual magnetization of the quiet chromosphere.

In order to investigate the magnetic sensitivity of the Hα linear polarization profile, we calculate response functions to the Hanle effect. In particular, we investigate the sensitivity of the emergent linear polarization profile of the Hα line to magnetic field perturbations.

As shown below, different parts of the Q/I profile are differently affected when the magnetic field is varied at a given height in the atmosphere. The response function provides valuable information on the quantitative reaction of the emergent linear polarization profile to the local magnetic field.

In Fig. 4 we show the Hanle response function of the Hα line in the (non-magnetic) FAL-C atmosphere to a perturbation in the strength of a horizontally oriented magnetic field with a random azimuth. In order to compute the response function, we have followed the same approach used by Uitenbroek (2006) field. Thus, the response functions of Q/I and of Q to perturbations in the magnetic field provide similar information.
by defining the response function of $q = Q/I$ as

$$R_b(\lambda, z) = \frac{1}{b} \frac{d}{dz} \langle \Delta q(\lambda) \rangle,$$

(1)

where $b$ is a small perturbation in the magnetic field ($b = 3$ G in our case) and $\Delta q(\lambda)$ is the modification of the emergent $q(\lambda)$ signal due to a perturbation applied up to the height $z$. Obviously, a key point is that to this end we apply a multilevel non-LTE radiative transfer code for the Hanle effect.

As seen in Fig. 4, the center of the $Q/I$ profile of H$\alpha$ is strongly reduced by a magnetic field enhancement in the upper layers of the chromosphere model, while it is practically unaffected below $z \approx 1700$ km. On the other hand, the polarization signal in the near wings at about $\pm 0.5$ Å from the line center can be slightly increased by enhancing the magnetic field at about $z \approx 1500$ km. Note that a magnetic field in the uppermost layers also affects the H$\alpha$ wings: this time it decreases the $Q/I$ signal.

A much more detailed analysis of the response function of H$\alpha$ to the Hanle effect will be presented in a forthcoming publication (Štepán & Trujillo Bueno 2009b; in preparation).

4. Conclusions

The Zeeman effect in H$\alpha$ is blind to the magnetic field of the upper layers of the quiet Sun. Fortunately, observations of linear polarization of the H$\alpha$ line close to the limb show a non-negligible signal in the line center. This is due to the anisotropic illumination of the hydrogen atoms in the upper chromosphere. Here we have shown that this scattering polarization signal is significantly modified by the presence of magnetic fields. The Hanle response function of the emergent $Q/I$ profile shows that the line core linear polarization observed close to the limb is exclusively sensitive to the magnetic fields in the uppermost layers of the chromosphere while the near wings can also be affected by magnetic fields in the lower chromosphere.

Careful spectropolarimetric observations and detailed radiative transfer modeling of the H$\alpha$ line profile can be used as a sensitive diagnostic tool of the magnetism of the quiet chromosphere, especially in its uppermost layers, providing us with valuable quantitative information on the magnetic field there (see Štepán & Trujillo Bueno 2009a; submitted).

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References

Bommier, V. & Sahal-Bréchet, S. 1982, Sol. Phys., 78, 157
Fontenla, J. M., Avrett, E. H., & Loeser, R. 1993, ApJ, 406, 319
Gandorfer, A. 2000, The Second Solar Spectrum: A high spectral resolution polarimetric survey of scattering polarization at the solar limb in graphical representation. Volume I: 4625 Å to 6995 Å, ed. A. Gandorfer
Landi Degl’Innocenti, E. & Landolfi, M. 2004, Polarization in Spectral Lines (Dordrecht: Kluwer)
Manso Sainz, R. & Trujillo Bueno, J. 2003, Physical Review Letters, 91, 111102
Sahal-Bréchet, S., Vogt, E., Thoraval, S., & Diedhiou, I. 1996, A&A, 309, 317
Schoolman, S. A. 1972, Sol. Phys., 22, 344
Socas-Navarro, H. & Uitenbroek, H. 2004, ApJ, 603, L129
Stenflo, J. 1994, Solar Magnetic Fields (Springer)
Trujillo Bueno, J. 2009, in ASP Conf. Series, Vol. 405, Solar Polarization 5, ed. S. V. Berdyugina, K. N. Nagendra, & R. Ramelli, 65
Trujillo Bueno, J. & Landi Degl’Innocenti, E. 1997, ApJ, 482, L183
Uitenbroek, H. 2006, in ASP. Conf. Series, Vol. 354, Solar MHD Theory and Observations: A High Spatial Resolution Perspective, ed. J. Leibacher, R. F. Stein, & H. Uitenbroek, 313