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Enigmatic magnetic field effects in the scattering polarization of the Ca I 4227 Å line

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Abstract. The scattering polarization of the Ca I 4227 Å line shows unexpected behavior in the presence of magnetic fields. Standard theory predicts the Hanle effect to be present in the line core, while it should disappear in the wings, where pure, non-magnetic scattering polarization is expected. Observations show however that even in the wings, far from the core, depolarization and rotation of the plane of linear polarization are sometimes present, in apparent contradiction with Hanle-effect theory.

1. Introduction

The observations were carried out with the 45 cm Gregory-Coudé telescope of IRSOL in Locarno (Switzerland) using the new UV-sensitive version of the ZIMPOL II polarimeter developed at the Institute of Astronomy of ETH Zurich (Gandorfer et al. 2002). The very fast polarization modulation of the beam (42 kHz for the circular polarization, 84 kHz for Stokes Q) effectively freezes the seeing to allow high precision polarization measurements (down to 10^{-5} in the degree of polarization). The initial aim of the observations was to confirm previous results obtained with a Semel-type double beam polarimeter, which showed Hanle effect signatures close to the limb (Bianda et al. 1997, 1999a,b). We here report unexpected results in active regions near the limb.

2. Observations

The observations were carried out in November and December 2001 with a set-up similar to the one used by Gandorfer (2000) for his atlas. The main difference was our use of a new UV-sensitive camera and new telecentric reduction optics with better transmission in the near UV. The modulator package consists of a piezoelastic modulator made from fused silica, and a Glan linear polarizer. The calibration optics for the violet part of the spectrum were not available at the time of these observations. Despite of this, the data could still be calibrated, as will be described below.

To avoid image drifts during the observations, the Primary Image Guider (PIG) was used (Küveler et al. 1998) in combination with a secondary image stabilizer (Sütterlin et al. 1997). The slit width of 200 μm corresponds to 1.6 arcsec. The spatial dispersion is 2.31 arcsec per pixel.

The exposure time was 5 s per frame. 16 such frames were added to obtain a stored image. A two phase observing mode was used (cf. Gandorfer et al. 2002) to correct for charge pocket effects in the CCD (cf. Gandorfer and Povel 1997 for details). One PEM modulator modulates one component of the linear and circular polarization simultaneously, but not Q/I and U/I simultaneously. An observation therefore consists of the following steps: After a recording of Q/I and V/I, the modulator package is rotated by 45° to record Stokes U/I and V/I. This is repeated 4 to 6 times, to increase the statistics. 100 dark frames, recorded with the same exposure time as used for the limb observations, are averaged to obtain the dark current image.

Two kinds of observation were done: (1) with the solar limb parallel to the spectrograph slit, to keep $\mu = \cos\theta$ constant along the slit, and (2) with the solar limb perpendicular to the slit, to directly obtain the center-to-limb variation of the different parameters.

3. Data reduction

The reduction of the ZIMPOL data is described in Gandorfer et al. (2002). To correct for cross talk the symmetry properties of the Zeeman signatures, combined with qualitative knowledge about the Hanle signatures, was used, as described in Stenflo et al. (2001). In some cases, as will be discussed later, Q/I signatures persist in U/I even after cross talk correction and cannot be explained in terms of instrumental effects.

Figure 1 gives an example of an observation, after cross-talk correction and wavelet smoothing of the four bidimensional Stokes images.

As mentioned in the previous section, the appropriate calibration UV optics were not available at the time of observation. To determine the polarization scale the center-to-limb variation (CLV) of the blue Q/I wing was scaled to fit the curve obtained with Eq. (1) in Bianda et al. (1999b), i.e., $Q/I = a(1-\mu^2)/(\mu+b)$ with $a = 0.33\,\%$ and $b = 0.002$. In Fig. 2 the analytical (dot-dashed) and the observed and scaled Q/I blue wing (solid line) CLV profiles are shown.

4. Results

Figure 1 shows a recording in an active region, obtained on December 19, 2001. The slit was perpendicular to the limb. The Stokes I panel shows the Ca I line with the blends. As the zero point of the spatial scale is at the limb, we can follow the CLV of the Stokes parameters 150 arcsec towards disk center. The Q/I linear polarization panel (white means polarization parallel to the solar limb) shows the expected strong increase towards the limb of the non-magnetic polarization in the Ca I wings and the transverse Zeeman effect patterns in the blend lines

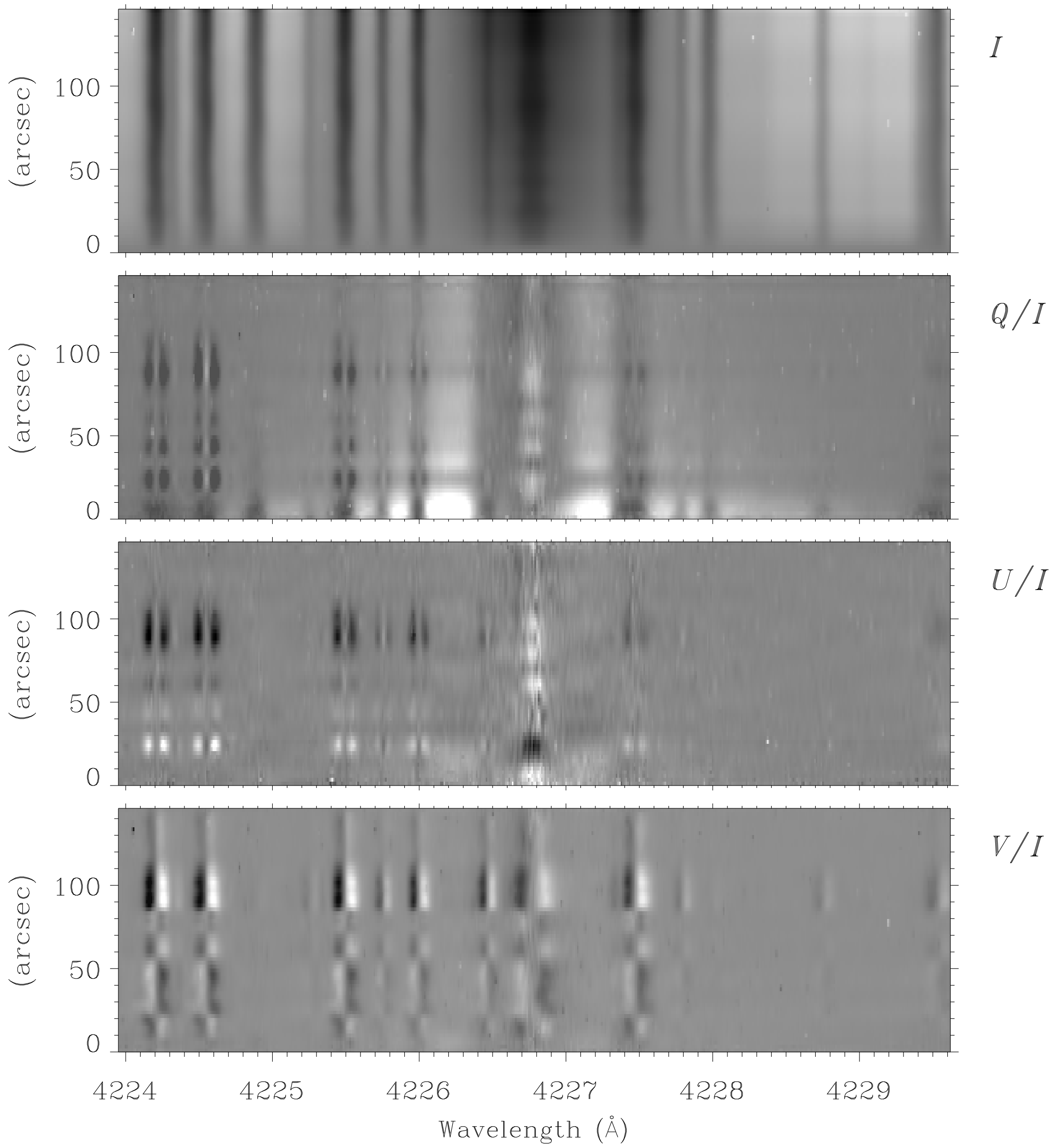

Figure 1. Images of the four Stokes parameters recorded with the spectrograph slit perpendicular to the limb. The zero point of the spatial scale corresponds to the solar limb. The field of view thus extends 150 arcsec inside the limb.

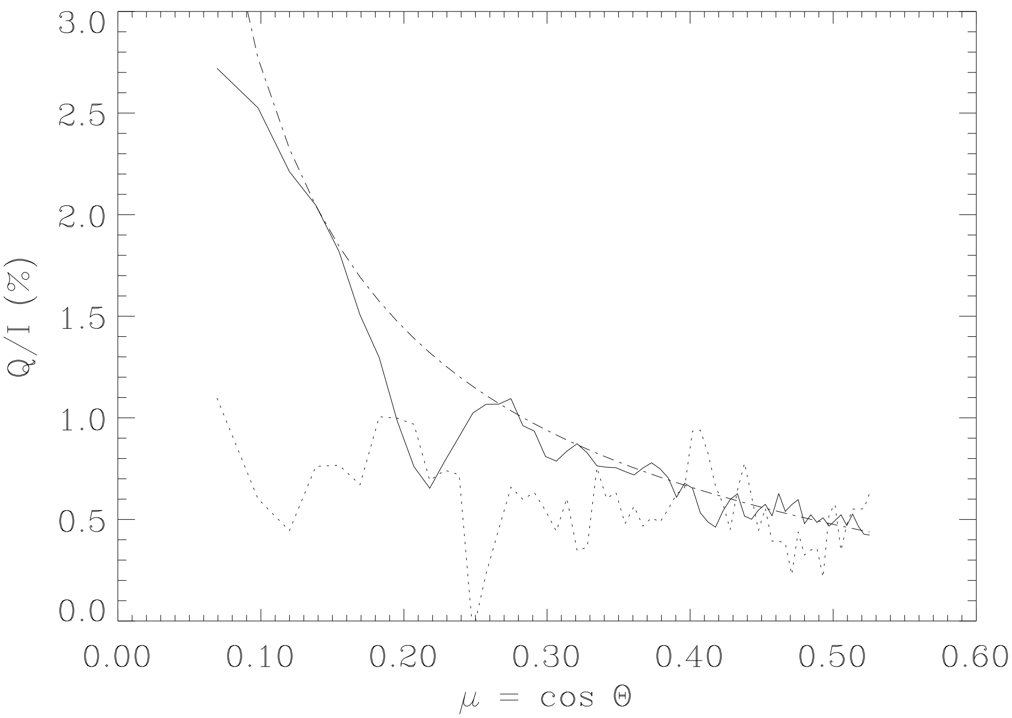

Figure 2. Center-to-limb variation of Q/I, derived from the observations in Fig. 1. Solid line: Blue-wing (4226.2 Å) maximum. Dotted line: Core peak maximum. Dot-dashed line: Analytical function representing the blue-wing maximum (see Sect. 3).

(except for the CH 4224.86 Å line, which only depolarizes near the limb). The core polarization is changing irregularly along the spatial direction, as expected from Hanle depolarization, due to local fluctuations of the magnetic field. The unexpected feature is the horizontal depolarizing strip 25 arcsec inside the limb, as will be discussed later. The U/I panel (linear polarization oriented 45° to the limb) shows transverse Zeeman patterns in the blend lines, as well as polarization in the Ca I line center caused by Hanle rotation of the plane of polarization. Note the qualitative difference between these Zeeman and Hanle signatures. Again we see enigmatic strips in the wings, which need to be explained. The V/I panel shows longitudinal Zeeman patterns but with absence of any signature in the CH line. Some minor artifacts introduced by the wavelet smoothing are present as minor striations in the core peak of the U/I panel.

Figure 2 shows the CLV of Q/I for the blue wing maximum (solid line) and the core peak (dotted line), while the dot-dashed line represents the analytical function mentioned in Sect. 3. We notice a large blue wing depolarization around $\mu \approx 0.22$, and possibly a small depolarization around $\mu \approx 0.42$. The wavelength variation of this Q/I depolarization is shown in Fig. 3. The depolarization feature seen in Fig. 2 is not an isolated case, but is confirmed by observations made in other active regions.

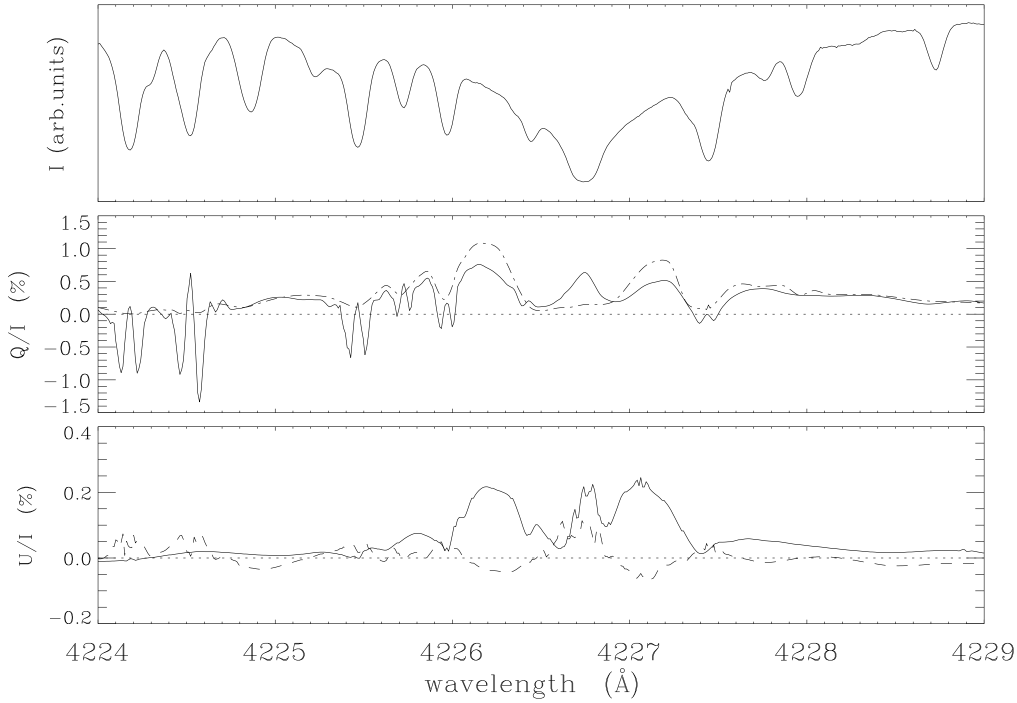

Figure 3. I, Q/I, and U/I profiles extracted from Fig. 1 at different μ values. The I profile refers to $\mu = 0.17$. The Q/I profiles refer to $\mu = 0.23$ (solid line) and $\mu = 0.26$ (dot-dashed line). The U/I profiles refer to $\mu = 0.15$ (solid line) and $\mu = 0.31$ (dashed line).

Spatial variations of the polarization peak at line center in active regions have been seen in previous observations with the double beam polarimeter (Bianda et al. 1999a). In quiet regions the ratio between the Q/I line center peak and the blue wing maximum was found to always be less than one (Bianda et al. 1997). Note however that the line center value at $\mu = 0.4$ is larger than expected: here we have an enhancement that is cospatial with the magnetic region in Fig. 1 at 80 arcsec from the limb (which corresponds to $\mu = 0.4$). A general and systematic correspondence between depolarization in the wings and the line center peak amplitude was not found, although there seemed to be a relation in most of our observations. In the case shown here the location of the line center maximum is shifted towards the limb relative to the maximum of the wing depolarization, but we have other observations that do not show such a shift.

When examining all our observations we however find a general relation: Depolarization in the far wings of the Ca I line is always accompanied by transverse Zeeman-effect signatures in the surrounding blend lines.

Figure 3 shows profiles of three Stokes parameters at certain spatial locations in the recording that was presented in Fig. 1. The I profile refers to a position 15 arcsec inside the limb ($\mu = 0.17$), while the two Q/I profiles refer to 25 arcsec ($\mu = 0.23$, solid line) and 35 arcsec ($\mu = 0.26$, dot-dashed line), i.e., to a depolarized and to a more normal quiet region. These profiles are very different in their Zeeman signatures and also differ in their line center polarizations (the dot-dashed curve shows strong core depolarization). Otherwise the two profiles have very similar shapes and asymptotically agree in the far wings. This supports a depolarization interpretation, in which the wing depolarization decreases as we move away from the line center. Two U/I profiles, observed 11 arcsec inside the limb, i.e., at $\mu = 0.15$ (solid line), and at 48 arcsec, i.e., at $\mu = 0.31$ (dashed line), exhibit a Q/I-type profile shape in the wings. Due to their complementary behavior (opposite signs) it is not possible to explain them in terms of instrumental cross talk (from Q to U), but their origin appears to be solar. This behavior is confirmed by many other examples. The interpretation in terms of Hanle rotation of the polarization plane is supported by the sign variations of this effect, since they correspond to both clockwise and anti-clockwise rotation.

5. Discussion

Standard theory predicts that magnetic fields affect the scattering polarization only in the Doppler core of the line (in the form of Q/I depolarization and rotation of the plane of polarization, which creates a U/I signal), while the wings should remain unaffected (Omont et al. 1973; Stenflo 1994 (p. 83)). In contrast we observe Q/I depolarization and rotation of the polarization plane in the Ca I wings. This apparent contradiction suggests that the theory for the Hanle effect in the solar atmosphere is not sufficiently understood and may be in need of revision.

A possible explanation could be that the Ca I Zeeman effect extends far into the wings, but observations in active regions far from the limb do not show any such behavior at all.

As an alternative to the Hanle effect, the Q/I wing depolarization might have an explanation in terms of either "geometrical" depolarization, meaning that the plane-parallel stratification of the atmosphere breaks down in magnetic regions, or enhanced collisional depolarization, which could occur if the density and thereby the collision rate becomes enhanced in certain magnetic regions (A. van Ballegoijen suggested such a possibility in the discussion after the conference presentation). Both these mechanisms are however unlikely to account for the observed U/I signatures. In principle the anisotropy in the illumination of the scattering Ca atoms could deviate locally from the anisotropy given by the limb-darkening function, such that the radial symmetry gets broken and the resulting plane of polarization for the scattered radiation is no longer perpendicular to the radius vector (i.e., parallel to the nearest solar limb). However, since the spatial resolution was modest (several arcsec) in our observations, the fluctuations in the local anisotropy have to be of fairly large scale and of relatively large amplitude to be able to produce observable effects. We see no fluctuations in the Stokes I images that could indicate such variations in the radiation field. Although we cannot presently rule out this possibility, we consider it to be an unlikely explanation.

Another possibility has to do with subtleties in partial frequency distribution (PRD) of radiative transfer. PRD contains combined contributions from frequency coherence (the R_{II} function) and complete frequency redistribution (the R_{III} function), which mix in a complex way in the presence of magnetic fields. In the case of a balanced mixture of R_{II} and R_{III} it is possible for the Hanle effect to appear in the wings, and this effect is larger when the angular dependence of the frequency redistribution is taken into account (Nagendra et al. 2002). Conceptually, the mechanism might be understood as follows: We first have radiative excitation at a frequency in the line core, followed by Hanle precession of the excited oscillator until a collision shifts the frequency (without destroying the atomic polarization) so that the emission occurs in the wings. The details of this possibility however needs to be explored for a realistic model system.

The reasons why we believe that instrumental effects cannot explain our observations are: The Q/I and U/I signatures are spatially localized and occur at different limb distances, where signatures of the transverse Zeeman effect are found. There is no clear relation with intensity. In active regions we have depolarization both outside and inside sunspots. The signatures described may be confined within a few arcsec, and, in the case of Q/I-like signatures in U/I, it is possible to find examples where the sign is changing over a few arcsec. Such localized instrumental effects have never been seen in other observations at other wavelengths. Another argument is that spatial scans (done by changing the slit position in steps of 5 arcsec) give consistent results, showing that the spatial location of the effect is tied to the Sun and not to the position on the detector or within the field of view. Therefore we believe that the described effects are of solar origin.

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