SF2A 2007
J. Bouvier, A. Chalabaev, C. Charbonnel (eds)

RESONANCE POLARIZATION OF THE SOLAR 455.4 NM *BAII* LINE: DIAGNOSTICS OF CHROMOSPHERIC MAGNETIC FIELDS

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Abstract. The BaII resonance line at 455.4 nm is formed in the low solar chromopshere. It is significantly linearly polarized outside active regions and close to the solar limb. This so-called resonance polarization is sensitive to the Hanle effect of weak magnetic fields. We report on numerical simulations of the intensity and resonance polarization profiles in the line and in the adjacent continuum, in the quiet solar atmosphere and we compare them to observations performed at the Jean Rosch refractor at the Pic du Midi Observatory. In the simulations we take into account non-LTE multilevel coupling, multiple scattering and partial frequency redistribution, and we neglect the hyperfine structure of the odd isotopes. This allows to model the central part of the line core and the wings quite well. Then we investigate the diagnostic potential of the line core polarization for weak unresolved magnetic fields in the low chromosphere. We find that the observed polarization rates are in good agreement with the simulations if we take into account the Hanle effect of weak magnetic fields on the order of 60 to 75 Gauss.

1 Introduction

It is now well known that magnetic fields play a crucial role in the physics of the solar chromosphere (Innes *et al.* 2005), however we miss direct reliable diagnostic tools for the measurement of the field. The Zeeman effect on chromospheric lines is not easily interpreted because most of the chromospheric lines are broad and formed under non-LTE conditions. Moreover, the field strength decreases from the photosphere to the chromosphere and the physical conditions are highly inhomogeneous so that the measurements of the Zeeman polarization requires high spatial and spectral resolution. In this context, the Hanle effect can provide a valuable diagnostic tool because it is sensitive to weaker fields than the Zeeman effect and it does not average out in the presence of unresolved mixed polarity fields. The Hanle effect affects lines formed by scattering of photons under anisotropic illumination by modifying their linear resonance polarization, it is thus well suited to chromospheric conditions.

Here we investigate the diagnostic potential of the resonance line of ionized barium at 455.4 nm. Its linear polarization has been recorded outside active regions at the Jean Rosch refractor of the Pic du Midi observatory by Malherbe et al. (2006). We use the same procedure as the one described by Faurobert-Scholl (1992), in order to compute the line intensity and polarization profiles without and with Hanle effect. In a first step we solve the statistical equilibrium equations for the populations of the atomic levels, coupled to the line and continuum transfer equations, but neglecting the polarization. This provides the optical depth in the line of interest and multi-level coupling terms in its source function. In a second step, we compute the line intensity and polarization with an equivalent two-level approach.

2 Non-LTE line modeling

The Barium atom has odd and even isotopes with slightly different atomic structures. The 134, 136 and 138 even isotopes (82.1% of the total number density) have no nuclear spin, i.e. no hyperfine structure, whereas the 135 and 137 odd isotopes have a nuclear spin $I = 3/2$, the hyperfine structure of their fundamental level is detectable (Rutten 1978), but we shall neglect it in this first work. Figure 1 shows the atomic model that we use, together with the allowed radiative transitions.

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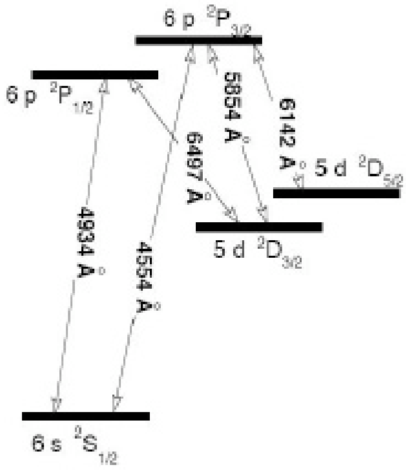

Fig. 1. Simplified atomic model of the BaII atom

The polarized radiative transfer equation that we solve for the 455.4 nm resonance line is written

$$\mu \frac{\partial \mathbf{I}_\nu}{\partial \tau_\nu} = \mathbf{I}_\nu - \mathbf{S}_\nu, \tag{2.1}$$

where μ is the cosine of the heliocentric angle of the line of sight, $\mathbf{I}_\nu$ is the 2-component vector $(I, Q)^\dagger$, where I is the specific intensity of the radiation field and Q is the Stokes parameter for the linear polarization, defined by $Q = I_r - I_l$, where I_r denotes the intensity on the radial direction and I_l the intensity in the direction parallel to the solar limb. The Stokes parameter U and V are vanishing in the absence of magnetic field and in the presence of a mixed polarity field. The vector $\mathbf{S}_\nu$ is the 2-component source function, given by

$$\mathbf{S}_\nu = \frac{\mathbf{j_c} + \mathbf{j}^{\mathbf{l}}_\nu}{k_c + k^l_\nu}, \tag{2.2}$$

where $\mathbf{j_c}$ and $\mathbf{j}^{\mathbf{l}}_\nu$ denote the emissivity in the continuum and in the line, respectively (notice that we take into account the continuum polarization due to Thomson and Rayleigh scattering), k_c and k^l_ν are the absorption coefficients in the continuum and in the line respectively. The line emissivity is detailed in Faurobert-Scholl (1992), in a two-level atom formalism. It is composed of 3 terms: a thermal emissivity, a term due to multi-level coupling, and a scattering term which gives rise to the linear polarization in the line. The scattering term is written

$$\mathbf{j_{sc}} = \int_0^\infty d\nu' \int \frac{d\Omega'}{4\pi} \hat{R}(\nu, \mathbf{n}, \nu', \mathbf{n}') \mathbf{I}(\nu', \mathbf{n}', z), \tag{2.3}$$

where the matrix $\hat{R}$ is the redistribution matrix of the polarized radiation field due to scattering processes. Its analytical expression is given by Domke & Hubeny (1988) and Bommier (1997), in the presence of collisions and of a weak magnetic field.

3 Results

3.1 Center-to-limb variations of the line intensity profiles

Figure 2 shows the comparison of the observed intensity profiles with the results of the non-LTE calculations for 3 models of the quiet solar atmosphere: the "standard" VALC model (Vernazza *et al.* 1981) where the temperature minimum between the photosphere and the chromosphere is located at $z = 500$ km above the basis of the photosphere; a so-called VALCm model, where the microturbulent velocity is set to 1 km/s in the photospheric layers, and the FALX model (Fontenla *et al.* 1993) where the temperature keeps decreasing up to z =1000 km. In order to fit the observed intensity profiles one has to take into account the effect of macroturbulent velocity fields in the solar atmosphere. This amounts to a smearing of the profiles by a normalized gaussian function with a width parameter. We assume typical values of the order of 3 km/s for the quadratic mean value of the macroturbulent velocities. We observe that the line width is sensitive to the value of the microturbulent velocity in the photosphere and that the VALm model allows a better fitting of the observations. However the observed line width is slightly underestimated by our model, presumably because we have neglected the hyperfine levels of the odd isotopes.

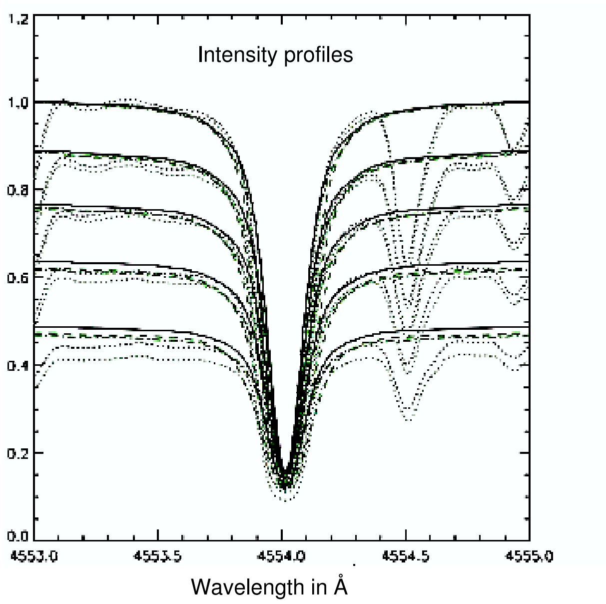

Fig. 2. Center-to-limb variations of the intensity profiles in the BaII 455.4 nm line and adjacent continuum. The observed profiles (dotted lines) are compared to the calculated ones for 3 atmospheric models: VALC: —- ; VALCm: - - -; FALX: - . -. From top to bottom the 5 sets of profiles correspond to 5 values of the line of sight heliocentric angle: $\mu = 0.5$; 0.4; 0.3; 0.2; 0.1. All the profiles are normalized by the continuum intensity at $\mu = 0.5$. The small aborption lines in the vicinity of the strong BaII line are not taken into account in the calculations.

3.2 Center-to-limb variations of the linear polarization

Figure 3 shows the comparison between the observed polarization rates (Q is divided by I) and the calculated ones for the same atmospheric models as in Fig. 2 and for several values of the line of sight heliocentric angle. The left-hand panel is devoted to non-magnetic cases whereas the right-hand one shows the depolarizing Hanle effect of weak magnetic fields. We find that the polarization is parallel to the solar limb (as observed) so the Stokes parameter Q is negative, so we prefer to plot $|Q|/I$, in order to deal with positive quantities.

Let us first notice that the polarization in the line core shows a triple peak feature which corresponds to the hyperfine structure of the line. As we neglected the hyperfine levels of the odd isotopes we obtain a single peak structure which can be compared to the envelope of the line core polarization. We find that, in the absence of a magnetic field, the observed polarization rate in the line core is significantly smaller than expected. This discrepancy can be due to the depolarizing Hanle effect of a weak unresolved magnetic field taking place in the low chromosphere where the line core is formed, a good fitting of the line core polarization envelope is obtained with $B = 60$ Gauss, when the model VALm is used, and with $B = 73$ Gauss for the other 2 atmospheric models.

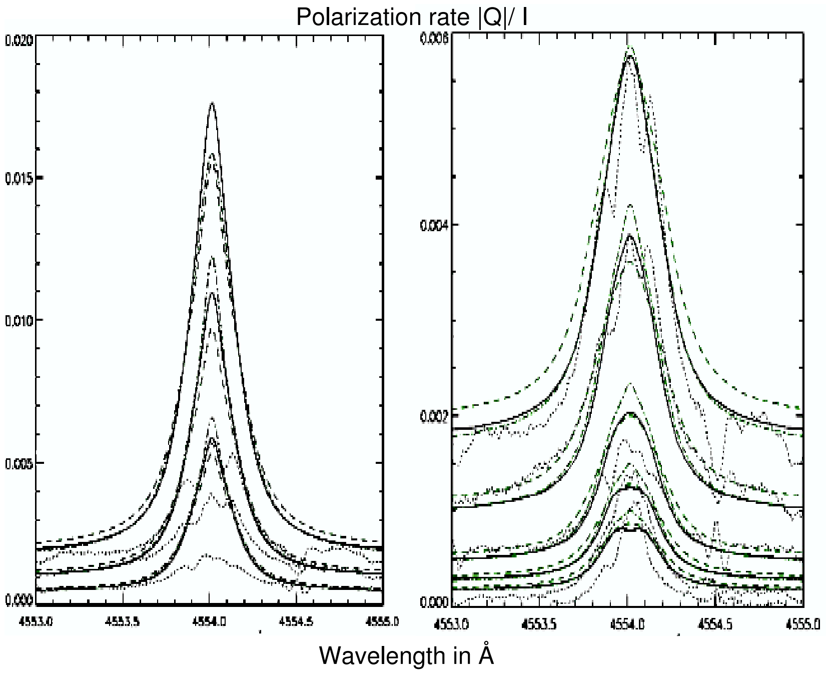

Fig. 3. Center-to-limb variations of the polarization rate profiles in the BaII 455.4 nm line and adjacent continuum. Left-hand fig.: magnetic field set to zero. From top to bottom the 3 sets of profiles correspond to 3 values of $\mu = 0.05$; 0.1; 0.2. The observed rates in dotted lines, are much smaller than the calculated ones for 3 atmospheric models: VALC: —- ; VALCm: - - -; FALX: - . -. Right-hand fig. (notice that the vertical scale is different): depolarizing Hanle effect of a weak turbulent magnetic field . From top to bottom the 5 sets of profiles correspond to 5 values of $\mu = 0.05$; 0.1; 0.2; 0.3, 0.4. Observed profiles: dotted lines, calculated profiles for VALC model and $B = 73$ Gauss: —- ; VALCm model and $B=$ 60 Gauss: - - -; FALX model and $B = 73$ Gauss: - . -.

4 Conclusions

The chromosphere is a highly inhomogeneous medium where temperature, velocity and magnetic fields have complex structures still poorly investigated. As the magnetic strength decreases with height in the solar atmosphere, the Hanle effect in resonance lines offers a valuable complement to Zeeman diagnostics. We have tested the sensitivity of the linear resonance polarization of the BaII 455.4 nm line to atmospheric conditions in the solar low chromosphere, such as microturbulent velocity fields and weak unresolved magnetic fields. This line is well suited for the diagnostics of weak magnetic fields on the order of a few tens of Gauss in this layer through the Hanle effect. Further observations should be performed to measure simultaneously the four Stokes parameters in the BaII line, in order to take advantage of both Hanle and Zeeman effects and get a complete view of the magnetic field structure.

References

Bommier, V. 1997, A& A, 328, 726

Domke, H. & Hubeny, I. 1988, ApJ, 65, 527

Faurobert-Scholl, M. 1992, A& A, 258, 521

Fontenla, J. M., Avrett, E. H. & Loeser, R. 1993, ApJ, 406, 319

Innes, D. E., Lagg, A. & Solanki, S. A. (eds.) 2005, Chromospheric and coronal magnetic fields, ESA SP596

Malherbe, J. M., Moity, J., Arnaud, J. & Roudier, Th., 2006, A& A, 462, 753

Rutten, R. J. 1978, Solar Phys.,56, 237

Vernazza, J.E., Avrett, E. H. & Loeser, R. 1981, ApJS, 45, 635