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RESONANCE LINE POLARIZATION IN MOVING OPTICALLY THICK STUCTURES

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Abstract. We compute the scattering polarization of lines formed in moving slabs of moderate optical thickness ($\tau = 1$ and $\tau = 10$) illuminated by a linearly polarized radiation field showing a broad absorption feature. Slabs are one-dimensional and horizontal, placed at a finite height H above a semi-infinite atmosphere. This model is an academic case which represents the formation of emergent radiation in solar filaments. The slabs have a macroscopic velocity in the radial direction with respect to the atmosphere, and are observed at different angles (i.e. at different locations over the solar disk). We investigate the sensitivity of the outgoing polarization to the slab velocity and observing angle. We show that outgoing polarization profiles are at least as sensitive to macroscopic velocity as are intensity profiles.

1. INTRODUCTION

Spectropolarimetric observations are extensively used in order to determine magnetic field strength via Hanle or Zeeman effect. For Hanle diagnostic, one is interested in scattering polarization which is a NLTE effect rising in dilute, scattering-dominated medium. Microtubulent magnetic field and depolarizing collisions further affect (i.e. decrease) polarization in the line. Another important diagnostic value of scattering polarization is that it gives us insight into the anisotropy of the radiation field which, in turn, is heavily influenced by the geometry of the emitting body. One of the first theoretical investigations of scattering polarization, both in slabs and in semi-infinite atmospheres, has been done by Faurobert (1987; 1988). She has shown the importance of taking into account partial frequency redistribution (PRD) for the modeling of resonance lines. She concluded that there is a significant difference between line polarization profiles obtained under assumptions of complete and partial frequency redistribution both in finite slabs and semi-infinite atmospheres. Furthermore, she found that the angle- averaged form of R_{II} redistribution (Hummer, 1962) yields similar results as the angle-dependent form. In these papers only self-emitting slabs have been considered.

However, modeling illuminated slabs of various optical thickness is important in solar physics. Prominences, filaments and spicules can be treated as 1-D or 2-D slabs which are illuminated by solar radiation from below and/or from the sides. The importance of partial frequency redistribution has been discussed plenty of times (see for example, Heinzel et al., 1987, or more recent, Labrosse et al. 2010). Also, the effects of the illuminated structure macroscopic motions have been discussed by several authors. First, Heinzel & Rompolt (1987) discussed the so-called "Doppler dimming" and "Doppler brightening" on hydrogen spectra in model prominences under the assumption of complete frequency redistribution (CRD). Later approaches included PRD (Gontikakis, 1997) and modeling UV helium spectra (Labrosse, 2007). It has been shown that doppler dimming can be a useful diagnostic tool for analysis of eruptive prominences. However, there have been no discussions on the effects of macroscopic velocity on emergent polarization profiles known to the authors of this paper.

In this paper we analyze the effects of the slab macroscopic motions on its outgoing line polarization. We consider 1D isothermal finite slab, placed at the height H above the isothermal, semi-infinite atmosphere which illuminates it from below. We use a two-level atom approximation with background continuum opacity. We account for partial frequency redistribution (which is important for strong resonance lines, formed in dilute medium) by using the R_{II} redistribution function, i.e. assuming coherent scattering in the atom reference frame. Instead of using some observed intensities as incident radiation, we compute the outgoing line radiation from a semi-infinite atmosphere, transform it to the slab co-moving frame and use it as a boundary condition for the radiative transfer problem in the moving slab.

This work is not intended to give a realistic description of a solar structure, but rather to inspect the effects of slab motion on emergent polarization profiles in the case when the moving slab is illuminated with a frequency dependent radiation field, in our case, with a strong absorption line.

2. RADIATIVE TRANSFER

Here we are interested in modeling scattering polarization in absence of large scale (resolved) magnetic field. In this regime, the polarization is a result of uneven population of Zeeman sublevels which is in turn result of the radiation field anisotropy. In the case where the radiation field is axially symmetric the intensity vector has only two components, $\hat{I} = (I, Q, 0, 0)^\dagger$. This is indeed the case in our model since the structure is illuminated from below. In the case where the illumination is coming from the sides, axial symmetry would be broken and one would have to deal with the azimuthal dependence of radiation field and to employ bit more complicated formalism. The optical depth scale is the same for the two components of the intensity vector and we can write the equation of polarized radiative transfer in vector form as:

$$\frac{d\hat{I}}{d\tau} = (\phi_\nu + \beta)(\hat{I} - \hat{S}), \tag{1}$$

where $\hat{S}$ is the source function vector, τ is the line-integrated optical depth, ϕ_ν the line absorbtion profile and β the continuum-to-line opacity ratio. For a two level atom , with continuum background, the source function vector can be written as the weighted sum of the line and continuum source functions,

$$\hat{S} = \frac{\phi_\nu \hat{S}_l + \beta \hat{S}_c}{\phi_\nu + \beta}. \tag{2}$$

Both line and continuum source functions are frequency dependent. We can write these two as,

$$\hat{S}_l(\mu,\nu) = (1-\epsilon)\frac{1}{2}\int_{-\infty}^{\infty}\int_{-1}^{1}\hat{P}(\mu',\mu)\hat{I}(\mu',\nu')g(\nu',\nu)d\mu d\nu' + \epsilon B_t \tag{3}$$

and

$$\hat{S}_c(\mu,\nu) = (1-\epsilon_c)\frac{1}{2}\int_{-1}^{1}\hat{P}(\mu,\mu')\hat{I}d\mu + \epsilon_c B_t, \tag{4}$$

where ϵ and ϵ_c are photon destruction probabilities in the line and in the continuum, respectively. Those to probabilities are given by

$$\epsilon = C_{\rm ul}/(C_{\rm ul} + A_{\rm ul}) \tag{5}$$

$$\epsilon_c = \kappa_{\rm abs}/(\kappa_{\rm abs} + \kappa_{\rm sc}). \tag{6}$$

Here $C_{\rm ul}$ is the rate of collisional de-excitation, $A_{\rm ul}$ is the Einstein coefficient of spontaneous emission, $\kappa_{\rm abs}$ the coefficient of pure absorption in the continuum and $\kappa_{\rm sc}$ the coefficient of scattering in the continuum. B_t is the Planck function and $\hat{P}(\mu,\mu')$ is the scattering phase matrix which can be written as,

$$\hat{P}(\mu,\mu') = \hat{P}_{is} + \frac{3}{8}W_2 W_B \hat{P}_2^0. \tag{7}$$

Here $\hat{P}_{is}$ is the matrix of isotropic scattering, W_2 is the intrinsic line polarizability, which is determined by the angular momentum of the line upper level depolarization, while W_B is the Hanle depolarization parameter. $\hat{P}_2^0$ is a phase matrix describing Rayleigh scattering, given by,

$$\hat{P}_2^0 = \begin{pmatrix} (\frac{1}{3}-\mu^2)(1-3\mu'^2) & (1-3\mu^2)(1-\mu'^2) \\ (1-\mu^2)(1-3\mu'^2) & 3(1-\mu^2)(1-\mu'^2) \end{pmatrix}. \tag{8}$$

The phase matrix in the continuum has a similar form, with $W_B = 1$ and $W_2 = 1$. Note that we are allowing for NLTE effects in the continuum, contrary to most test problems where the continuum source function is treated as equal to the Planck function. $g(\nu',\nu)$ is the so-called frequency redistribution function which is a result of partial coherence between incident and scattered photon in scattering process.

Solving Eq. (1) coupled with the Eq. (2) is a well known problem in polarized radiative transfer, which can be solved in the variety of ways. We use the following approach: We first solve the *scalar* radiative transfer problem and then we proceed to computing the source function vector in polarized case. For the scalar part, we use the forth-and-back implicit lambda iteration method developed by Atanacković et al. (1997). We use R_{II} distribution function computed with Ayres' aproximation (Ayres, 1985). After obtaining values for the scalar source function $S(\tau,\nu)$ we proceed to solve the polarized problem with an iterative scheme, solving in turn equations (1) and (2) until convergence. This method works fast for CRD problems, it is also applicable for

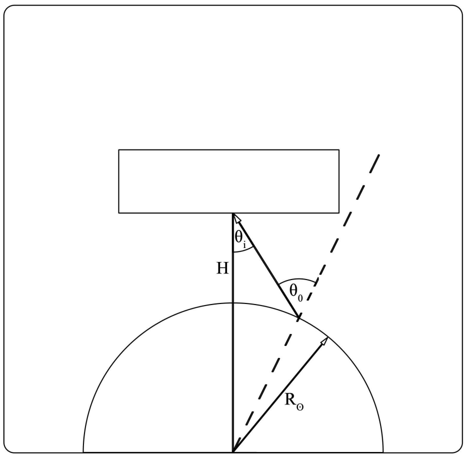

Figure 1: Geometry of the problem.

angle-averaged PRD case, but fails for angle-dependent PRD. In our computations, we use the angle averaged form of R_{II} and we obtain convergence in less than 10 iterations. If the angle- dependent form is considered, one should use either a direct Feautrier method, or PALI method, developed by Faurobert-Scholl et. al (1997) and subsequently generalized to PRD case by Paletou & Faurobert-Scholl (1997).

In order to solve the radiative transfer problem in the slab, we need boundary conditions, i.e. the illuminating radiation field. As illuminating radiation we use the emergent intensity vector from a semi-infinite atmosphere. We then transform that radiation to the reference frame of the moving slab. Transformation of the outgoing radiation field to the radiation field as "seen" by the prominence is described by the following equations:

$$\mu_i = (1 - \frac{R^2}{(R+H)^2}(1-\mu_o^2))^{\frac{1}{2}} \tag{9}$$

$$\nu_i = \nu_o(1 - \frac{v}{c}\mu_i) \tag{10}$$

where i and subscript refers to the incident radiation field, in the slab reference frame, serving as a boundary condition for solving radiative transfer in the slab, while o subscript refers to the outgoing radiation from the semi-infinite atmosphere, in the atmosphere (i.e. observer) reference frame. It is assumed here that slab has uniform, vertical velocity v directed radially. Figure 1 illustrates the geometry of the problem. After computing emergent radiation in slab reference frame, we need to return to the reference frame of the observer:

$$\nu = \nu'(1 + \frac{v}{c}\mu), \tag{11}$$

where ν and ν' are frequencies in observer and slab reference frame, respectively, and μ is cosine of angle between direction of ray propagation and normal to the slab.

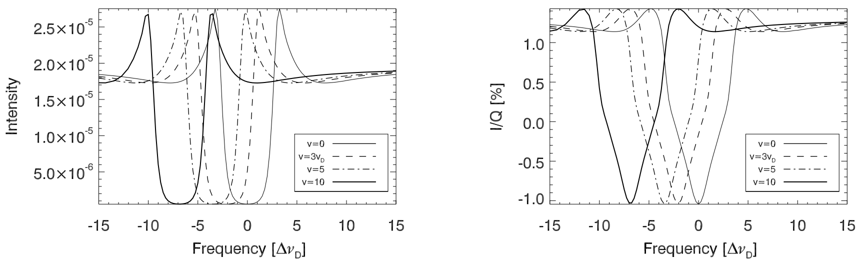

Figure 2: Incident intensity and linear polarization profiles as seen from the slab reference frame at $\mu_i = 0.69$.

3. RESULTS

In this section we present results for the simple test case of an isothermal atmosphere and isothermal slab. As incident radiation we use the outgoing intensity vector from the 1D semi-infinite atmosphere, computed with R_{II} frequency redistribution function, with a Voigt parameter $a = 10^{-3}$, $\epsilon = 10^{-4}$, $\beta = 10^{-5}$ and $\epsilon_c = 0.1$. We neglect the Hanle effect ($W_B = 1$). Since the atmosphere is isothermal and scattering is dominant, the emerging line is in absorption, with a very dark core.

Figure 2 shows the incident line profile as "seen" by the moving slab at the $H = 50000\,\mathrm{km}$ for different velocities, at $\mu_i = 0.69$. Essentially, it is the emergent line profile shifted by the Doppler effect.

We computed the emergent scattering polarization for slabs of total optical depth $T = 1$ and $T = 10$, with vertical velocities $v = 0, 3, 5$ and $10\,v_D$, where v_D stands for the thermal Doppler broadening in the moving slab. In the slab, we set $\epsilon = 10^{-6}$ and $\beta = 0$. We also assume that the temperature is identical for both the atmosphere and the slab. The slab is placed at height $H = 50000\,\mathrm{km}$. Note that, as the slab stands at some non-zero height, the incident field is very anisotropic, which should lead to a significant increase in the polarization signal. This can be seen from Fig. 3, as even in the case when there is no slab motion, the emerging polarization signal is very strong as compared to the incident polarization. Increasing the slab velocity leads to a very interesting effect, while the contribution of the line is negligible to the outgoing intensity (outgoing intensity is actually either just transmitted or scattered light from the atmosphere plus some absorption in the slab, blue-shifted due to the slab motion), one can see that the contribution of the slab to the polarization is significant. It is obvious in the case when $v = 10v_D$ where the polarization profile has two peaks. One is actually the same as the incident peak, while the other one is emitted by the slab, and blue-shifted due to slab velocity. Similar effects are also seen when the optical thickness of the slab is larger (see Fig. 4). There is of course a bigger contribution of the slab to the total emergent intensity, but its contribution to the emergent linear polarization is much more important.

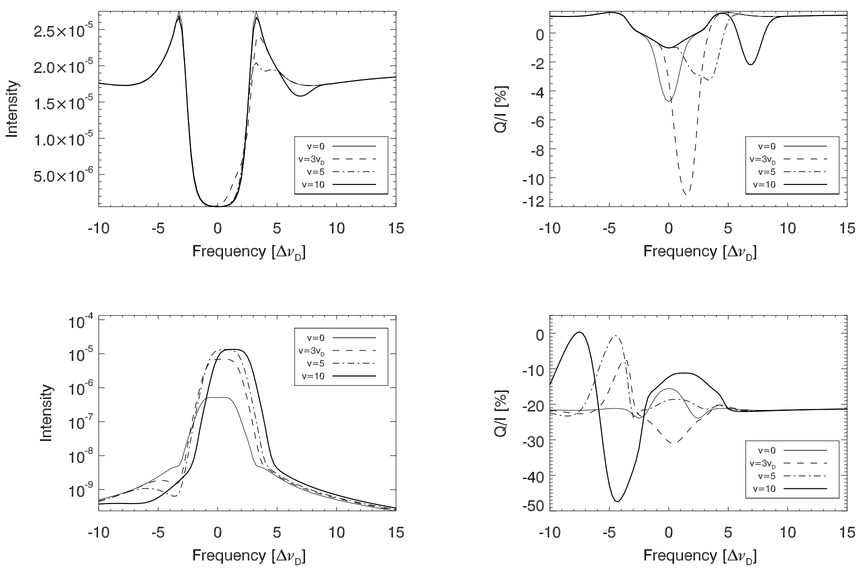

Figure 3: Outgoing intensity and polarization profiles for slab with $\tau_{\rm total} = 1$ and $H = 50000\,$km. *Top two panels:* Intensity and linear polarization profiles for μ=0.69; *Bottom two panels*: Intensity and linear polarization profiles for $\mu = 0.13$.

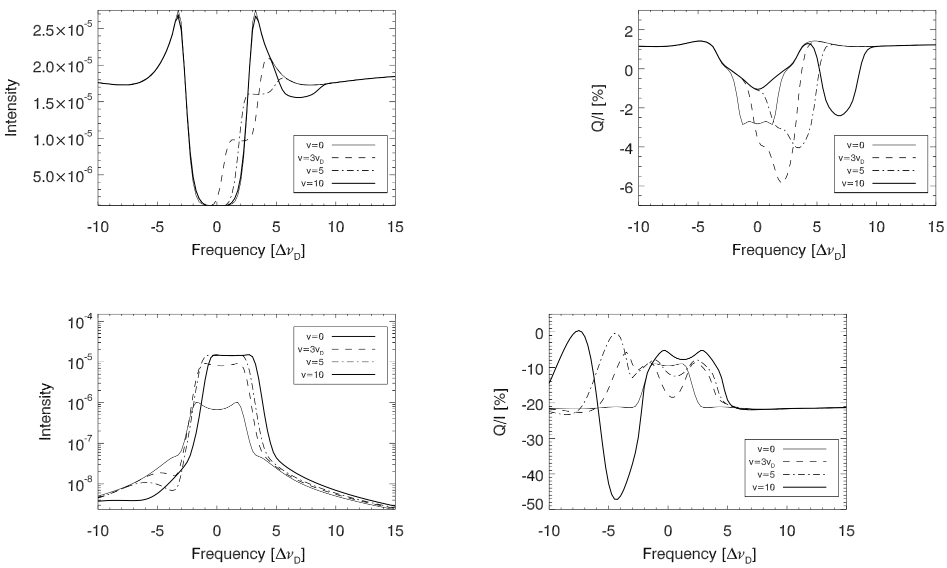

Figure 4: Same as figure 3 except total optical depth of the slab is 10.

4. CONCLUSION

In this work we investigated line scattering polarization profiles emerging from moving slabs of moderate optical thickness illuminated by the radiation from a semi-infinite atmosphere. Both in the slab and in the atmosphere the line is formed with R_{II} partial frequency redistribution. The polarization profiles emerging from the slab are much more sensitive to velocity effects than intensity profiles. It is important to note that, as the slab stands at some height above the atmosphere, the anisotropy of the incident radiation is increased and so is the scattering polarization of the radiation emerging from the slab. Macroscopic velocity then leads to very prominent changes in the polarization profile, this could easily be used as a diagnostic tool for eruptive filaments. However, since we have used a simple 1-D model, we are currently unable to predict if this will stay valid if one wants to turn to 2-D geometry. Filaments or spicules are clearly at least two-dimensional in terms of radiative transfer problems, so for consistent comparison with the observations, more sophisticated models should be used.

Our future plans are directed toward generalizing the radiative transfer method to two-dimensions and then more realistic modeling of some known lines such as Ca I 424.7 nm and CaII 854.2 nm. A multilevel atom approach will also be implemented.

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