Polarimetry: From the Sun to Stars and Stellar Environments
Proceedings IAU Symposium No. 305, 2014
K. N. Nagendra, S. Bagnulo, R. Centeno &
M. J. Martínez González, eds.

doi:10.1017/S1743921315004834

Inhomogeneity and velocity fields effects on scattering polarization in solar prominences

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Abstract. One of the methods for diagnosing vector magnetic fields in solar prominences is the so called "inversion" of observed polarized spectral lines. This inversion usually assumes a fairly simple generative model and in this contribution we aim to study the possible systematic errors that are introduced by this assumption. On two-dimensional toy model of a prominence, we first demonstrate importance of multidimensional radiative transfer and horizontal inhomogeneities. These are able to induce a significant level of polarization in Stokes U, without the need for the magnetic field. We then compute emergent Stokes spectrum from a prominence which is pervaded by the vector magnetic field and use a simple, one-dimensional model to interpret these synthetic observations. We find that inferred values for the magnetic field vector generally differ from the original ones. Most importantly, the magnetic field might seem more inclined than it really is.

Keywords. Polarization, line: formation, Sun: prominences

1. Introduction

It is almost certain now that magnetic fields are responsible for the formation and evolution of chromospheric objects such as prominences and spicules. Diagnostics of these magnetic fields gives us a way of comparing theoretical models with observations. However, magnetic field is not a quantity which is available for the direct measurement. Instead, we have to observe polarization in magnetically sensitive spectral lines and then go through the process of probabilistic inference to get some idea about the magnitude and orientation of the magnetic field. Such a process relies on an assumption of a specific generative model (parameter inference in solar spectropolarimetry is usually referred to as "inversion", and we will use that expression from now on), which is, due to the relatively complicated physics of spectral line formation, usually highly simplified. In particular, generative models always rely on one-dimensional geometry, i.e. it is assumed that the object is inhomogeneous only along one coordinate. Emergent Stokes spectrum then depends on a relatively small number of parameters (<10), and, by choosing an appropriate procedure which minimizes the difference between observed and computed spectra, we hope to infer the parameters "responsible" for the observed spectrum. This is the idea behind commonly used inversion codes such as ones described by Lagg *et al.* (2004) and Asensio Ramos *et al.* (2008). These codes are commonly applied on the observations of 10830 Å line of Helium as it is quite strong, exhibits large degree of scattering polarization ($\approx 1\%$) and is sensitive to the Hanle and Zeeman effect of the magnetic field of ≈ 10 Gauss which is the value we expect to find in solar prominences. These lines are, however, possibly opaque enough to allow for significant radiative transfer effects in these objects.

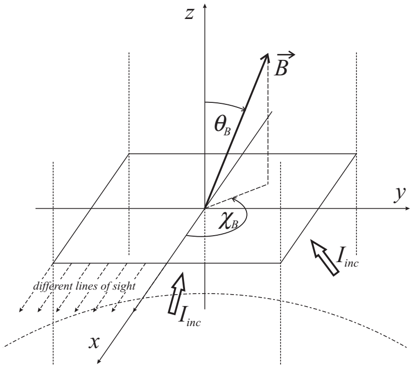

Figure 1. Geometry of the prominence model described in Section 2

In this contribution we study the effects of spatial inhomogeneities on the process of polarized line formation. Our main point is that the line formation process is significant, when the lines are optically thick enough, multidimensional, and thus sensitive to opacity inhomogeneities and velocity fields. Attempting to interpret observations which are, in fact, generated via this complicated multidimensional model by using a 1D slab model could, in principle, lead to systematic errors and misdiagnosis of the magnetic field vector. To investigate these errors we compute Stokes spectrum of a prototype spectral line emerging from a two-dimensional, inhomogeneous and dynamic slab representing a solar prominence. We then set-up a simple inversion procedure which relies on a one-dimensional generative model and depends only on few parameters, and use it to "interpret" these synthetic observations.

In the next section we quickly recap the models of the prominence and the scattering atom and the numerical method used for the computation of the polarized spectra.

2. Computation of emergent Stokes spectrum

The prominence is represented by a vertical 2D slab, inhomogeneous and finite along x and y and homogeneous and infinite along z, where z axis coincides with the atmospheric normal (Fig. 1). The slab is illuminated from the sides with limb-darkened continuum radiation obeying quadratic limb-darkening law corresponding to wavelength of $\approx 10000\,\text{Å}$. Angles θ and φ describe the direction of propagation of radiation. The line of sight of "observations" corresponds to $\theta = \pi/2$ and $\varphi = 0$. The slab is assumed to lie $20''$ ($\approx 15000\,\text{Km}$) above the solar surface. The height of the slab is an important parameter as it influences the degree of anisotropy of the incoming radiation.

Emergent Stokes spectrum is determined by the prominence model itself, the model of scattering atoms and finally, the boundary conditions for the equation of radiative transfer. In this contribution we focus on the first aspect, while simplifying the atomic model as much as possible, that is, we use a simple two-level atom model. The mechanism responsible for the spectral line polarization is the anisotropic illumination of the scattering atoms, which leads to the uneven population of so-called Zeeman sublevels of the upper level of the transition, which, in turn leads to the linear polarization of the scattered (i.e., re-emitted) photons. This effect is further modified by the presence of the vector magnetic field which changes the degree and the angle of polarization (Hanle effect). In the case of an optically thick plasma, to predict emergent spectrum we must self-consistently solve the radiative transfer equation (here given in 2D Cartesian geometry):

$$\frac{d\hat{I}(x,y,\theta,\varphi,\lambda)}{d\tau} = \phi(\lambda)\left[\hat{I}(x,y,\theta,\varphi,\lambda) - \hat{S}(x,y,\theta,\varphi)\right], \tag{2.1}$$

and the equation of statistical equilibrium for a two level atom:

$$\hat{S}(x,y,\theta,\varphi) = \hat{W}\int_{-\infty}^{\infty}\phi(\lambda)d\lambda \oint \frac{\sin\theta d\theta d\varphi}{4\pi} \times \hat{P}(\theta,\varphi,\theta',\varphi')\hat{I}(x,y,\theta,\varphi,\lambda). \tag{2.2}$$

Here τ is the line-integrated optical path "along-the-ray" (that is, along a given direction), $d\tau = \chi_l ds$ where ds is elementary geometrical path along the ray and χ_l is so called line-integrated opacity. ϕ is line absorption profile, which describes the dependence of the opacity on the wavelength, while $\hat{I}$ and $\hat{S}$ are polarized intensity and source function (ratio of emissivity and opacity), respectively. Finally $\hat{P}$ is the scattering matrix which, in the case of two-level atom, corresponds to Rayleigh's scattering matrix and $\hat{W}$ is a matrix which accounts for effects of intrinsic line polarization and magnetic fields (see Anusha & Nagendra 2011a,b). For the prototype line considered in this paper we have chosen the intrinsic line polarizability W_2 to be equal to 0.3, inverse radiative lifetime of the upper level $A_{ul} = 1 \times 10^7$ s and a Landé factor of 1.5 which leads to the critical value of the magnetic field of the Hanle effect of 0.76 G. These atomic parameters lead to the degree of polarization and magnetic sensitivity similar to the red wing of the He 10830 Å line.

We solve coupled Eqs. (2.1) and (2.2) by using real reduced intensity formalism developed by Anusha & Nagendra (2011a,b) (see also following papers by same authors). The signal in Stokes V is due to the longitudinal Zeeman effect only and, since the magnetic field throughout the prominence is assumed to be constant and weak, it can be computed from Stokes I only:

$$V(\lambda) = -4.39 \times 10^{-13}\lambda^2 g B_n \frac{dI}{d\lambda}, \tag{2.3}$$

where λ is expressed in Å and B_n is line-of-sight component of the magnetic field, expressed in Gauss. We neglect the transversal Zeeman effect due to the fact that, in this case, the Hanle effect acting on scattering polarization is much more important.

We now demonstrate the effects of multidimensional radiative transfer and spatial inhomogeneities.

3. Magnetic field free example

In the absence of the magnetic field, non-zero Stokes Q and U are the consequence of the angular anisotropy of the radiation field. In the quiet Sun, for example, we observe scattering polarization in spectral lines because the scattering atoms are illuminated with limb-darkened radiation field. This results in non-zero Stokes Q. In observations with poor spatial resolution we do not see any Stokes U as the inhomogeneities sort of "cancel out", but in spatially resolved observations this might not be the case (see Štěpan 2015, these proceedings).

Situation with prominences is similar: a one-dimensional, magnetic field-free model of the slab would result in the signal in Stokes Q and zero signal in Stokes U. Multidimensional model, accounting for inhomogeneities and radiative transfer effects, however, predicts non-zero Stokes U as well. We demonstrate this on a toy model of a prominence consisting of multiple (in this case 20) threads, each with a macroscopic velocity. The prominence is 2000 km "thick" and 10000 km "wide". The threads are represented by Gaussian over-densities with centers randomly distributed over the slab. Each thread

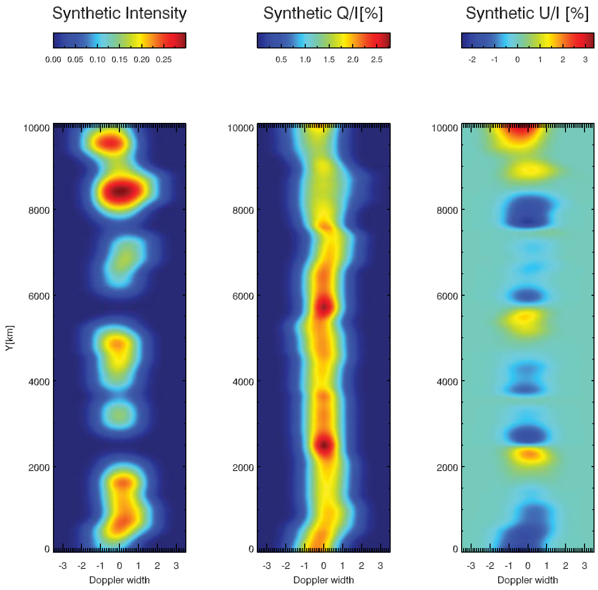

Figure 2. Synthetic polarized spectra resulting from a prominence model given in Section 3 (color version in on-line copy of this figure).

has a macroscopic velocity equal to the Doppler velocity of the gas with a random orientation in x, y plane and $z-$ component of the velocity equal to zero. All the threads are identical and the maximum opacity of each thread is chosen such that the "mean" line-of-sight line-integrated optical depth, which we define as:

$$\overline{\tau}_{los} = \frac{\int_0^{x_{\rm total}} \int_0^{y_{\rm total}} \chi_l(x,y) dx\, dy}{y_{\rm total}}, \tag{3.1}$$

is equal to 2. This is far from the optically thick case, but this opacity still allows for significant amount of scattering and radiative transfer effects inside the slab.

Fig. 2 shows the spectral and spatial variation of the emergent intensity and scattering polarization. By emergent we mean: intensity in the direction $\theta = \pi/2$, $\varphi = 0$, at the face of the slab, i.e., $x = x_{\rm total}$. We have smoothed the spatial distribution of the polarized intensity with a $0.5''$ (≈ 400 Km) wide Gaussian filter in order to simulate limited resolving power of today's instruments.

Random distribution of the opacity and the macroscopic velocity results in the highly variable Stokes I, which closely follows the opacity distribution. Line width is also variable, due to different directions of the thread macroscopic velocity. Stokes Q varies with location, and it generally anti-correlates with Stokes I. Reason for this is the following: In more opaque regions increased number of scattering decreases the anisotropy of the radiation field, thus reducing signal in Stokes Q. This reasoning can be reproduced even with 1D models (Milić *et al.* 2015, in preparation). However, one-dimensional models cannot predict highly variable signal in Stokes U (see the rightmost panel of Fig. 2). This signal is only due to the azimuthal anisotropy of the radiation field, which is, in turn the consequence of the scattering of the photons in an inhomogeneous medium. An attempt to interpret this signal as being due to the magnetic field would most probably fail, as the total degree of polarization is higher than predicted by the one-dimensional models. Another feature that we want to draw attention to is the "edge effect", i.e., the large degree of scattering polarization in Stokes U near the left and right edge of the slab. This

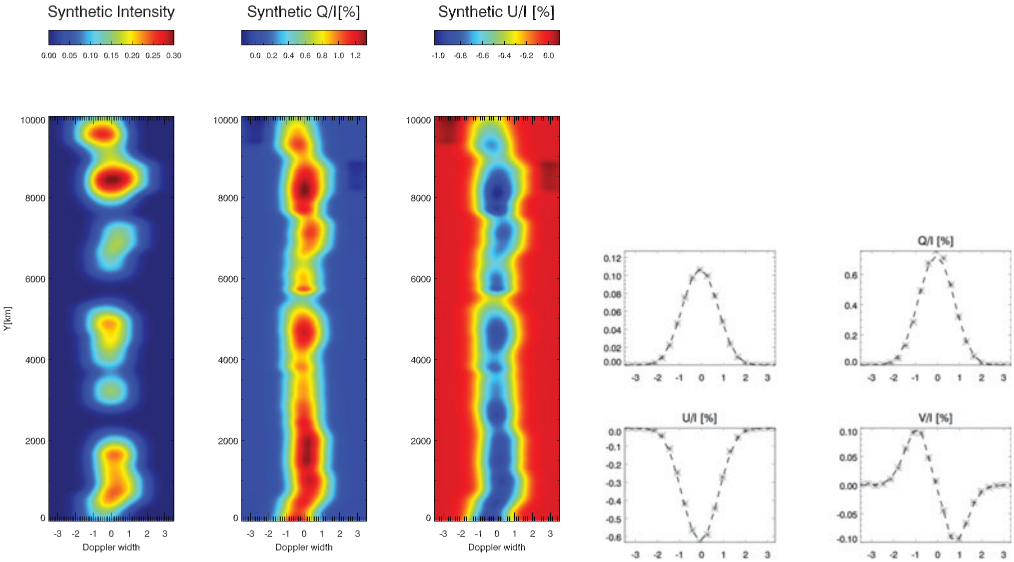

Figure 3. Left: Same as Fig. 2, but now also involving Hanle effect of the magnetic field with parameters $B = 10\,$Gauss, $\theta_B = 30°$ and $\chi_B = 150°$ (color version in on-line copy of this figure). Right: Inversion of polarized profile emerging at $y = 7000\,$Km.

is, again, the consequence of the anisotropy of the radiation field near the edges of the slab. These are present even in the homogeneous models and exist purely because of the radiative transfer effects.

4. Inversion of synthetic observations

In this section we will add a magnetic field to the prominence model described in Section 3. The magnetic field has the magnitude of 10 Gauss, with inclination of $\theta_B = 30°$ and azimuth $\chi_B = 150°$. This inclination is much smaller then the "canonical" value (it is generally accepted that prominence magnetic fields are close to being horizontal), but we are about to illustrate an important effect (see below). Also, the idea of this work is to show importance of multidimensional radiative transfer in inhomogeneous media so it should be applicable to wider class of objects (e.g. solar spicules). The emergent polarized spectrum computed in the presence of the magnetic field is given in Fig. 3.

It is evident that the distribution of the scattering polarization is now much more homogeneous along the y axis. To really discuss the eventual effects of our inhomogeneities and multidimensionality on the emergent spectrum we must attempt to "invert" the synthetic spectrum and see if there are significant differences between the input magnetic field and the inferred one. Due to the limited scope of this paper we pinpoint only one emergent spectrum, one emerging from the "blob" located at $y = 7000\,$km. Prior to the inversion, we add to the spectra a very low level of Gaussian noise, corresponding to a S/N ratio of 2×10^4. To invert the Stokes spectrum we use a simplification of the model given in Section 2:

- Model is 1D rather than 2D. That is, the slab is homogeneous and infinite both in y and z.
- Unpolarized source function is constant inside the slab and is considered to be a free parameter.

- All the components of the polarized source function are considered to be dominated by the Stokes I.

Under these assumptions, the emergent Spectrum is described by a generative model which involves the following parameters: line-integrated optical depth of the slab, thermal velocity of the line, line-of-sight velocity of the slab, value of the unpolarized source function in the slab, and three parameters describing the magnetic field vector. Fig. 3 (right) shows the best fit for the polarized profile at $y = 7000\,\mathrm{Km}$. The inferred values of the parameters of interest are: $B = 8\,\mathrm{G}$, $\theta_B = 60^\circ$ and $\chi_B = 163^\circ$. The most important result is that the inferred value of the magnetic field inclination is significantly higher then the input value. It is evident that the more complicated, multidimensional and inhomogeneous model predicts polarized spectrum which cannot always be reliably inverted using a simple 1D model, that is.

5. Conclusions

In this contribution we have attempted to illustrate the effects of inhomogeneities and the importance of multidimensional radiative transfer in the formation of polarized spectral lines in solar prominences. On a relatively simple toy model of a multi-thread prominence, we have demonstrated that significant amount of polarization in Stokes U can arise simply because of the inhomogeneities in the medium. Subsequently, we have computed a synthetic spectrum for a prototype line formed in such a prominence model, in the presence of the magnetic field and then inverted the synthetic spectrum using a simple 1D generative model. The differences between input and inferred values for the magnetic field are non-negligible. Most importantly, the inferred magnetic field is much more inclined than the magnetic field used for the original computations. This suggest that, inversion of the Stokes spectrum of lines which are opaque enough to allow for significant amount of scattering and radiative transfer might suffer from systematic errors.

In the future we plan to first undertake a statistical study, i.e., to invert all the synthetic spectra, for different prominence toy models and then to repeat this investigation by using more realistic atomic model for the formation of He 10830 Å along with one of the publicly available inversion codes. Such an investigation would truly indicate eventual presence of the systematic errors in current approaches to inversion of prominence spectra. What is, nevertheless, to be concluded is the following: polarized line formation in multidimensional media is a complicated process and we cannot hope to gain understanding of physical quantities and information contained in these lines by relying only on one-dimensional inversions (see also contributions by Štépan 2015 and Tichý *et al.* 2015, in these proceedings).

Acknowledgements

This research has been partially supported through the research project 176004, “Stellar physics” of Serbian Ministry of science and education. IM also wants to thank IAU for the travel grant for attending the symposium.

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