Advances in Plasma Astrophysics
Proceedings IAU Symposium No. 274, 2010
A. Bonanno, E. de Gouveia Dal Pino & A.G. Kosovichev, eds.

doi:10.1017/S1743921311007150

Inclusion of velocity gradients in the Unno solution for magnetic field diagnostic from spectropolarimetric data

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Abstract. We present an extension of the Unno-Rachkovsky solution that provides the theoretical profiles coming out of a Milne-Eddington atmosphere imbedded in a magnetic field, to the additional taking into account of a vertical velocity gradient. Thus, the theoretical profiles may display asymmetries as do the observed profiles, which facilitates the inversion based on the Unno-Rachkovsky theory, and leads to the additional determination of the vertical velocity gradient. We present UNNOFIT inversion on spectropolarimetric data performed on an active region of the Sun with the french-italian telescope THEMIS operated by CNRS and CNR on the island of Tenerife.

Keywords. Sun: magnetic fields, polarization, line: profiles, radiative transfer, methods: numerical.

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1. Introduction

Many observations of solar Stokes profiles show asymmetries that can be well explained by depth gradients in the line-of-sight velocity (Auer & Heasley, 1978 and Landolfi & Landi Degl'Innocenti, 1996). Fourier Transform Spectrometer (FTS) observations at disk center (Stenflo *et al.*, 1984) have shown that Stokes V profiles have larger blue lobes than red, indicating the presence of such gradients, if we exclude other explanation related to non-LTE effects (Solanki, 1986; Pantellini *et al.*, 1988). Sanchez, Almeida & Lites (1992) showed that the observations can be reproduced by postulating sufficiently large vertical velocity gradients. We present an extension of the Unno-Rachkovsky solution (Landi Degl'Innocenti & Landolfi, 2004) that provides the theoretical Stokes profiles taking into account a vertical velocity gradient. Thus, the theoretical profiles may display asymmetries as do the observed profiles, which facilitates the inversion based on the Unno theory, and leads to the additional determination of the vertical velocity gradient.

2. The Unno theory modified for velocity gradients

We present a modelling involving a flow inside a magnetic element with a gradient along the line of sight to reproduce the observed asymmetry. The comparison between the modelling and observations leads us to call in question again the hypothesis of a stationary flow inside the magnetic element. The first reason is that the stationary flow doesn't describe the behavior of the mean slope bisector that is proportional to the velocity gradients. Secondly, Ribes *et al.* (1985) as well as Solanki & Pahkle (1988) show that the calculated profiles fail completely to match the observations especially in the

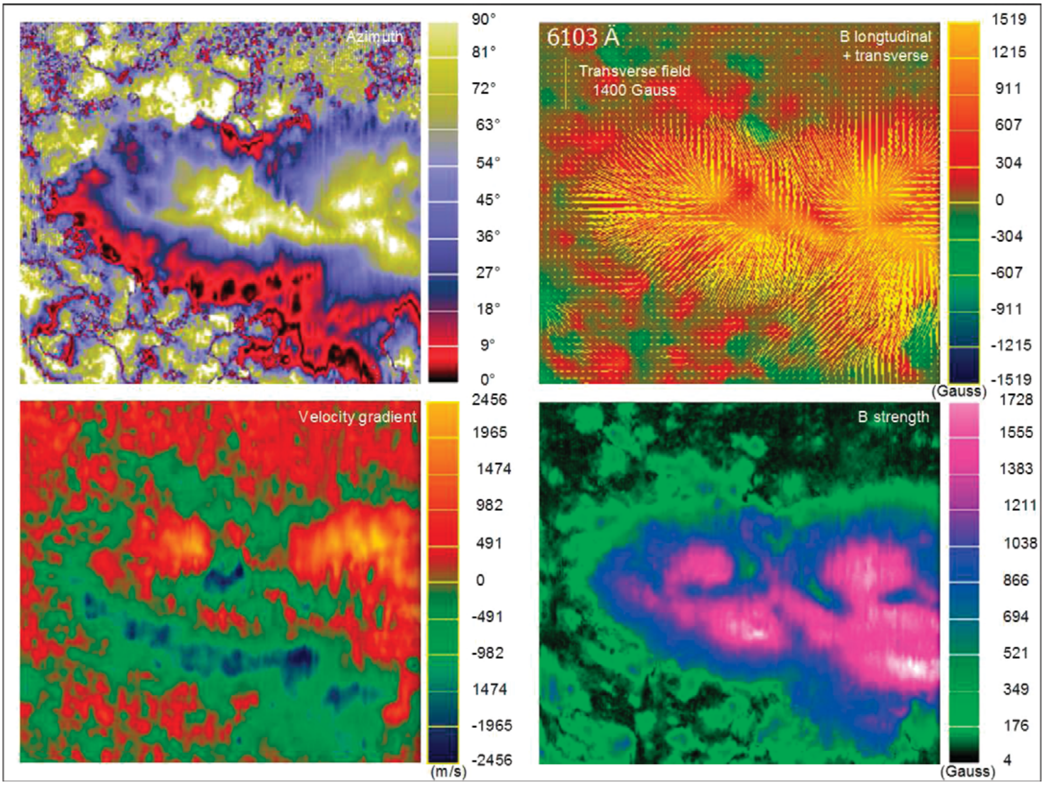

Figure 1. UNNOFIT inversion code applied on sunspot observed the 20^{th}, August 2008 at THEMIS for ion Ca I 6103 Å. Top left: horizontality of the field vector; Top right: The longitudinal magnetic field component displayed in color and the tranverse magnetic field in dashed lines (Gauss). Bottom left: The additional determination of the vertical velocity gradients is displayed and expressed in ms^{-1}. Bottom right: The magnetic field derived in terms of local average field strength (Gauss).

comparaison of lines with different stengths and excitation potentials. A systematical comparison between the modelling and observations leads us to allow to the velocity gradient a wavelength distribution function proportional to the profile itself in order to keep the linear behavior of the observed mean bisectors as noticed by J. Rayrole (Molodij & Rayrole, 2006). We have implemented this extension in the UNNOFIT Milne-Eddington inversion code. We propose the following modification of the theory.

We modified the absorption coefficient entering the Unno-Rachkovsky formalism, Unno (1956), Rachkovsky (1961). To generalize the transfer equations to account for the magnetic field splitting in the presence of a velocity field gradient, we propose the following modification of the quantities $\eta_{p,l,r}$ that denote the ratio between the line absorption and the continuous absorption for Zeeman triplets.

Let be v_r the radial velocity at the line center formation depth and v_h the Zeeman shift expressed both in Doppler width unit to match to the different observed line profiles:

$$\left\{ \begin{array}{ll} v_r & = \alpha \, \frac{v_s}{\xi} \\ v_h & = \frac{4{,}67.10^{-2} \lambda^2 \bar{g} H}{\xi} \end{array} \right. \tag{2.1}$$

where v_s is the velocity expressed in ms^{-1}, $\bar{g}$ is the effective Landé factor, α a constant to convert the velocity in Doppler width unity ξ. Introducing the velocity gradient δ_V

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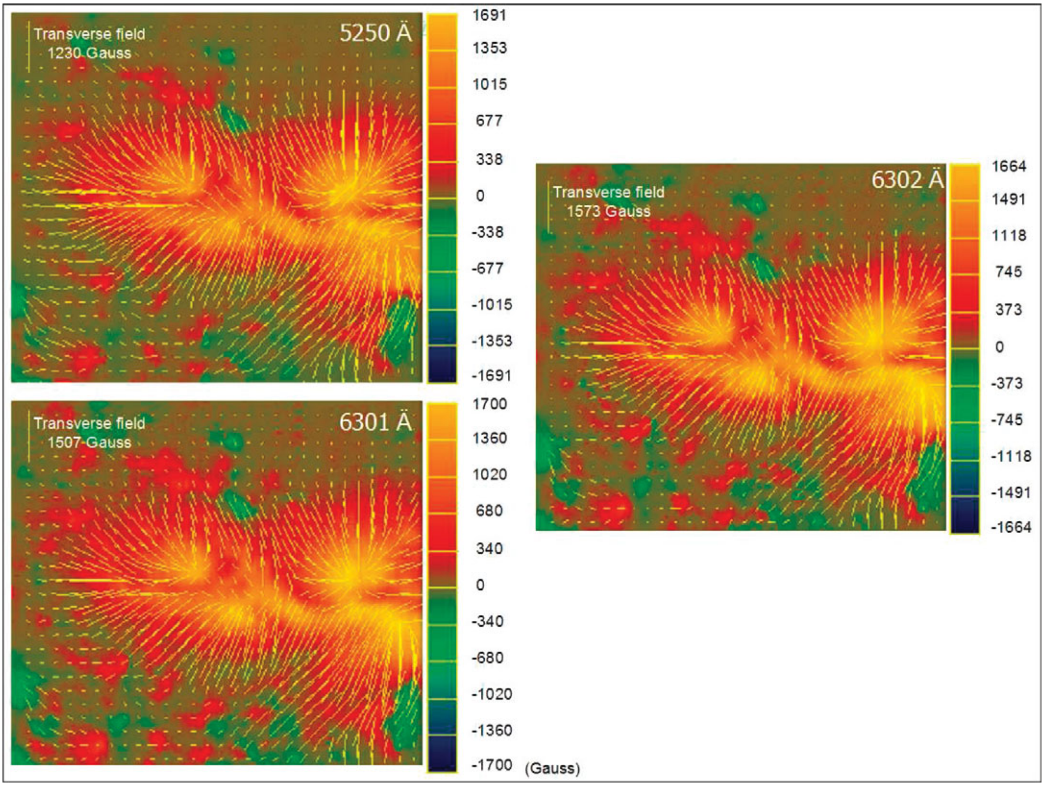

Figure 2. UNNOFIT inversion code applied on sunspot observed the 20^{th}, August 2008 at THEMIS for ions Fe I 6301 Å, Fe I 6302 Å and 5250 Åsimultaneously observed. We obtain a tomography of the 3D shape of the magnetic field depending on the height of formation of the different lines of the solar atmosphere.

(indeed, velocity difference between the line center and far wings formation depths), one obtains the absorption coefficients $\eta_{p,l,r}$ respectively for each of the π, σ_+ and σ_- components:

$$\begin{cases} \eta_p &= \eta_0 \; e^{-\left(\frac{\lambda-\lambda_0}{\xi}+v_r+\delta V_p\right)^2} \\ \eta_l &= \eta_0 \; e^{-\left(\frac{\lambda-\lambda_0}{\xi}-v_h+v_r+\delta V_l\right)^2} \\ \eta_r &= \eta_0 \; e^{-\left(\frac{\lambda-\lambda_0}{\xi}+v_h+v_r+\delta V_r\right)^2} \end{cases} \tag{2.2}$$

with:

$$\begin{cases} \delta V_p &= \frac{\delta_V}{\xi} \; e^{-\left(\frac{\lambda-\lambda_0}{\xi}+v_r\right)^2} \\ \delta V_l &= \frac{\delta_V}{\xi} \; e^{-\left(\frac{\lambda-\lambda_0}{\xi}-v_h+v_r\right)^2} \\ \delta V_r &= \frac{\delta_V}{\xi} \; e^{-\left(\frac{\lambda-\lambda_0}{\xi}+v_h+v_r\right)^2} \end{cases} \tag{2.3}$$

3. UNNOFIT inversion icluding velocity gradients

We inverted a spectropolarimetric scan of a sun spot region achieved with THEMIS on 20, August 2008 in the line Ca I 6103 Å. We use the UNNOFIT code of Bommier *et al.* (2007) improved by introducing the velocity gradient parameter. The tests run show that the inversion is faster and reproduce successfully asymmetries modelled with the velocity

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gradients assumption. Figure 1 displays the magnetic field solution of the UNNOFIT procedure. The field vector is drawn in terms of longitudinal (in colors) and transverse (in dashes) components. These components are expressed in the line-of-sight and plane of the sky coordinates. The magnetic field can be derived in terms of local average field strength and horizontality of the field vector. We show an additional determination of the vertical velocity gradients.

4. Conclusion

We have performed UNNOFIT inversion on spectropolarimetric data obtained for CaI 6103 Å on a sunspot. UNNOFIT is an inversion code (Landolfi *et al.*, 1984) that includes the magneto-optical and damping effects (Landolfi & Landi Degl'Innocenti, 1982) and that is based on the Marquardt algorithm applied to the Unno-Rachkowsky solution and modified to take into account the velocity gradient for the Stokes parameters emerging from a Milne-Eddington atmosphere. UNNOFIT was complemented by introducing a two-component atmosphere, having a magnetic and a non-magnetic component (Bommier *et al.*, 2007). We modified the absorption coefficient entering the Unno-Rachkovsky formalism in order to derive the theoretical profiles. The theoretical profiles display asymmetries as do the observed profiles, which facilitates the inversion based on the Unno-Rachkovsky theory, and leads to the additional determination of the vertical velocity gradient. An interest of the present work us to provide 3D plot of the local average magnetic field for simultaneously observed lines as displayed in figure 2.

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