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Spectropolarimetric analysis of 3D MHD sunspot simulations

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We have employed 3D non-grey MHD simulations of sunspots to compute theoretical Stokes profiles and compare the levels of circular and linear polarization in the simulations with those observed in a real sunspot. We find that the spatial distribution and average values of these quantities agree very well with the observations, although the polarization levels in the simulations are slightly larger. This can be explained by a slightly larger magnetic field strength or a larger temperature gradient in the simulated penumbra as compared to the observations.

1 Introduction

Recent radiative 3D MHD simulations of full sunspots (Scharmer, Nordlund & Heinemann 2008; Rempel, Schüssler & Knölker 2009; Rempel et al. 2009) reveal a complex picture of the penumbra where convective flows in the presence of an inhomogeneous magnetic field are channeled along the more inclined field lines becoming the Evershed flow. This convective flow transports enough energy to sustain the penumbral brightness and produces intensity patterns that are in qualitative agreement with observations at high spatial resolution (Scharmer et al. 2002; Sütterlin, Bellot Rubio & Schlichenmaier 2004). However, the previous observations refer to wavelength integrated intensities over certain filters (G-band) or monochromatic wavelengths, whereas in fact spectropolarimetric observations, that provide a much better constraint, are also available but have never been compared with the aforementioned simulations.

In this paper we address this point and perform a quantitative and qualitative comparison between the polarimetric signals (Stokes profiles) arising from these simulations and those observed by the spectropolarimeter on-board of the Japanese spacecraft Hinode (Tsuneta et al. 2008; Ichimoto et al. 2008). As a first step we consider only the wavelength integrated values of Stokes V (circular polarization) and Stokes Q and U (linear polarization).

2 Stokes synthesis from sunspot simulations

The sunspot simulations we have used for our analysis are those from Rempel et al. 2009b. These are 3D MHD simulations of a sunspot pair (with opposite polarities) using the MURaM code (Vögler et al. 2005) with the modifications described in Rempel et al. 2009a. The size of the simulation box is $98{\times}49\times6.1$ Mm (with the last number corresponding to the vertical direction) with a resolution of $32\times32\times16$ km. The simulations span 1 hour of real solar time evolution using grey-radiative transfer. After this time, non-grey radiative transfer (using the opacity binning method with 4 bins) is switched on for 15 minutes. Employing non-grey radiative transfer is crucial to obtain realistic temperature stratifications in the layers above $\tau = 1$ and therefore needed for spectral line computations (Shelyag et al. 2007). From the last snapshot of the temporal evolution, we have selected a penumbral region (440×320 pixels) of one of the sunspots. This region shows (see right first-row panel in Fig. 1) relatively well formed penumbral filaments.

The simulation provides the 3 components of the magnetic field and velocity vectors, as well as the temperature, gas pressure and density for every pixel (x, y) of the simulation and at every height (z). In order to locate the selected region at any heliocentric angle Θ, and at any azimuthal angle Ψ within the sunspot, we follow a similar procedure to that described in Borrero, Bellot Rubio & Müller (2007) and Borrero & Solanki (2010). This allows us to calculate the stratifications of the different quantities (temperature, magnetic field strength and inclination, LOS-velocity, etc.) along any ray-path for a given viewing angle. Once these have been obtained we employ the synthesis module of the SIR inversion code (Ruiz Cobo & del Toro Iniesta 1992) to solve the radiative transfer equation and obtain the polarization signals (Stokes I, Q, U, V) for the magnetic sensitive ($g_{\rm eff} = 2.5$) spectral line Fe I 6302.5 Å.

3 Comparison with Hinode/SP observations

In order to compare with Hinode/SP observations we must decrease the resolution of the simulated Stokes profiles to

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the resolution of the observations. This is done by first applying the Point Spread Function (PSF) of the SP instrument (Danilovic et al. 2008), and then by rebinning the original 440×320 array into a 146×106 array to provide a similar number of pixels per unit area as the CCD of the SP instrument. From the resulting Stokes profiles we compute maps of the continuum intensity, circular and linear polarizations, which are then compared with similar maps obtained from spectropolarimtric observations, recorded with Hinode/SP, of the Fe I 6305.5 Å spectral line, in the active region AR 10924 observed on 2006 November 14 very close to disk center: $\Theta = 8\overset{\circ}{.}6$. Within this active region, we have selected a patch that lies next to the line-of-symmetry of the sunspot in the limb-side penumbra: $\Psi = \pi$. Note that these two values of Θ and Ψ are the ones that were employed to compute the ray-paths and the synthetic Stokes profiles from the simulations (see Sect. 2).

Figure 1 shows maps of the continuum intensity (first row), circular polarization (second row) and linear polarization (third row) levels in the Hinode/SP sunspot observations (left) and the simulated one (right). A number of similarities and can be immediately seen: both simulations and observations show large bubbles (with about 10–15% of circular polarization) in the umbra. Here, the simulated and observed linear polarization are in both cases small due to the mainly vertical magnetic fields present in the umbra. In the simulated and observed penumbra, the structures become more radial and filamentary, with typical values of about 5–7% in the circular polarization and of 10% or more in the linear polarization. In the outer simulated and observed penumbra, the circular polarization displays the so-called *neutral line*[1], which is characterized by very small values of the circular polarization (<1%).

The continuum intensity maps are rather different. The simulations show radial filaments that are shorter (by a factor of two) as the observed ones. In addition, the intensity in the observed filaments is rather homogeneous, whereas in the simulations the intensity in the penumbral filaments presents larger changes. These differences could be explained by the relatively young age of the simulated penumbra (only 1 hour). The fourth row in Fig. 1 shows histograms for the circular (left) and linear (right) polarization but restricted to the penumbral only (defined by selecting those pixels with continuum intensities between 0.4 and 0.8). As it can be seen the average linear polarization in the simulations is larger than in the observations (8.8% and 6.8%, respectively). It is less clear however, that the same happens in the circular polarization: 4.1% in the simulations versus 3.6% in the observations. Performing the Kolmogorov-Smirnov test yields a 87% probability that both circular polarization histograms were obtained from the same probability distribution functions. This percentage is only 40% for the linear polarization. However, this percentage goes up to 72% if we shift the histograms to have the same average values.

Interestingly, the ratio circular to linear polarization remains very similar, which indicates that the inclination of the magnetic field vector is very similar in the simulated and observed penumbra. The larger polarization levels (both circular and linear) in the simulations could then be due to a larger field strength or a steeper temperature drop in the simulated penumbra as compared to the observed one. To study this possibility it is necessary to perform inversions of the simulated profiles to retrieve the full magnetic field vector and compare it with the observations.

[1] The *neutral line* indicates regions where the magnetic field is perpendicular to the observer.

4 Conclusions

In spite of the obvious differences in the continuum intensity and size between the simulated penumbra and observed penumbra, the recent 3D MHD sunspot simulations carried out by Rempel et al. (2009a, 2009b) present polarimetric properties that compare very well to those of real sunspots: quantitative and qualitative levels of circular and linear polarization agree very well. This indicates that these simulations posses an overall magnetic configuration that is very similar to that of a real sunspot in the photosphere. In the future we will carry out a more detailed analysis using the full shape of the Stokes profiles instead of its wavelength integrated values, as well as calculating the full magnetic field vector as inferred from the inversion of the theoretical Stokes profiles. In addition, we plan on using longer runs to study whether the sunspot develops a more mature penumbra that could help to explain the differences in the continuum intensity we see at this point.

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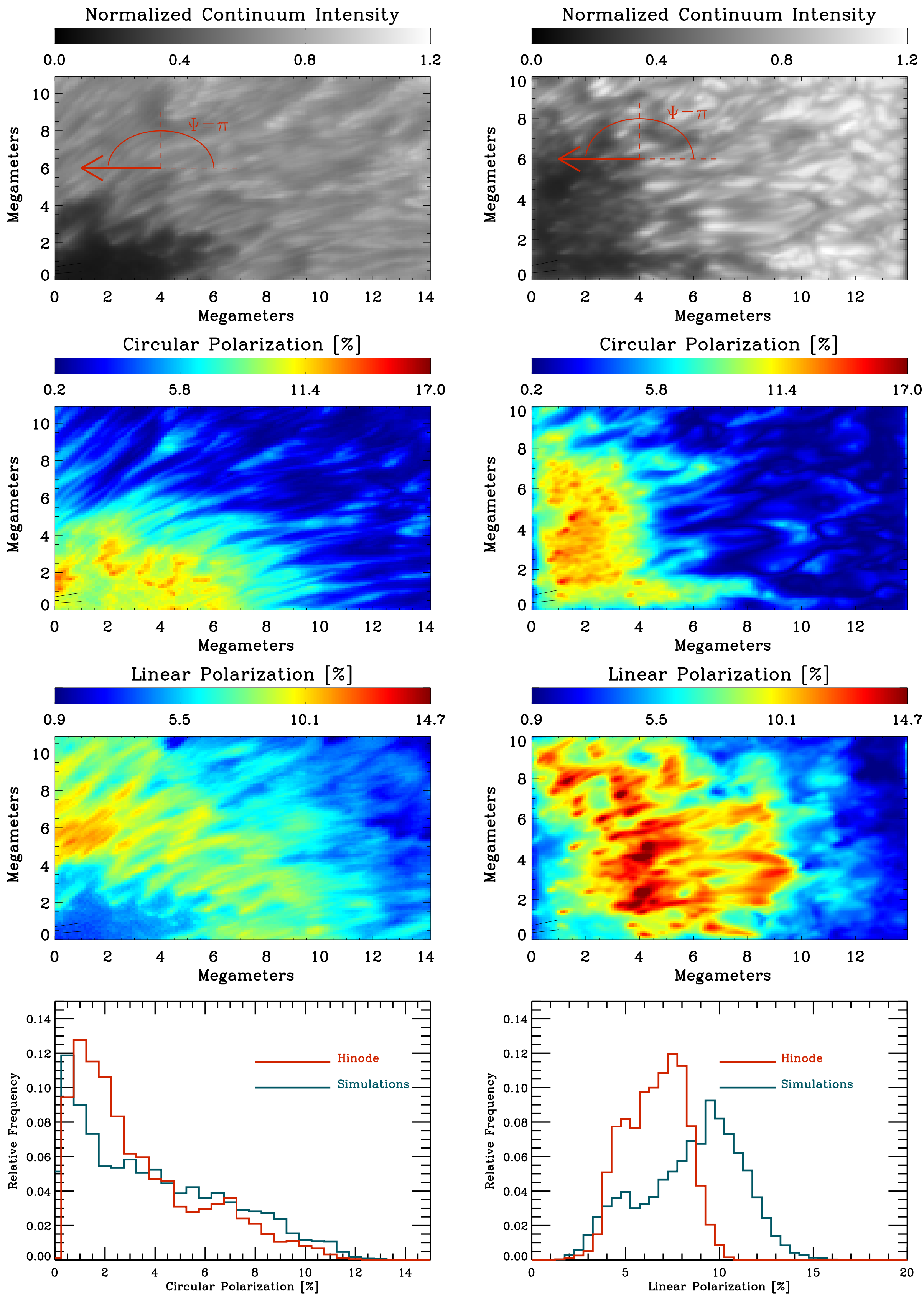

Fig. 1 (online colour at: www.an-journal.org) Continuum intensity (*first row*), circular polarization (*second row*), linear polarization (*third row*) maps in Hinode/SP observations from AR10940 ($\Theta = 8.^{\circ}6$; *left panels*) and simulations from Rempel et al. 2009b (*right panels*). The red arrow in the continuum intensity map indicates the direction of the center of the Solar disk. The bottom panels histograms for the circular (left) and linear (right) polarization for the penumbral pixels alone.