

Photospheric Magnetic Fields of the Trailing Sunspots in Active Region NOAA 12396

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Abstract. The solar magnetic field is responsible for all aspects of solar activity. Sunspots are the main manifestation of the ensuing solar activity. Combining high-resolution and synoptic observations has the ambition to provide a comprehensive description of the sunspot growth and decay processes. Active region NOAA 12396 emerged on 2015 August 3 and was observed three days later with the 1.5-meter GREGOR solar telescope on 2015 August 6. High-resolution spectropolarimetric data from the GREGOR Infrared Spectrograph (GRIS) are obtained in the photospheric lines Si I λ 1082.7 nm and Ca I λ 1083.9 nm, together with the chromospheric He I λ 1083.0 nm triplet. These near-infrared spectropolarimetric observations were complemented by synoptic line-of-sight magnetograms and continuum images of the Helioseismic and Magnetic Imager (HMI) and EUV images of the Atmospheric Imaging Assembly (AIA) on board the Solar Dynamics Observatory (SDO).

1. Introduction

The present study extends the work by Verma et al. (2016), where we presented a detailed description of observations and data analysis for one of the datasets taken as part of a coordinated observing campaign in August 2015. In the initial study, the results from the one-component inversions were discussed and were complemented with the SDO observations. Here, we show results from two-component inversions.

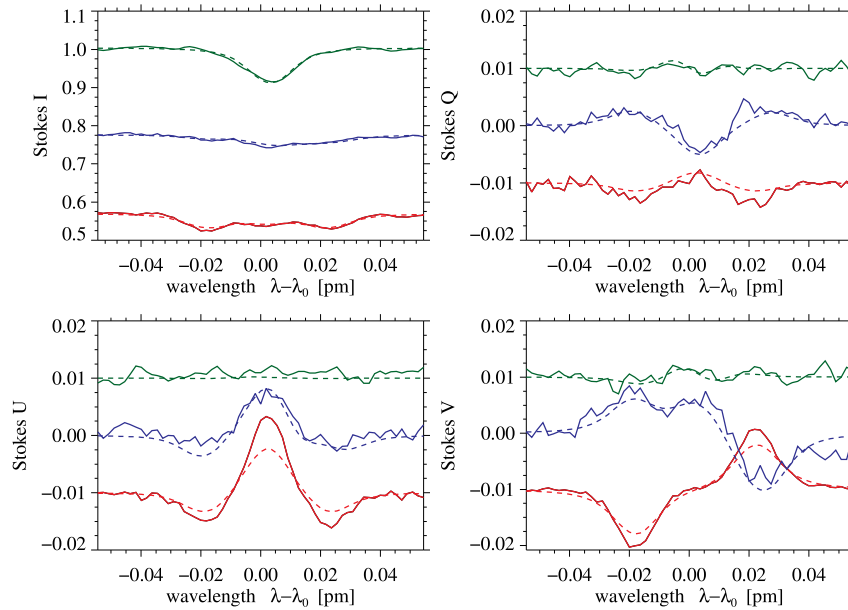


Figure 1. All four Stokes profiles of the photospheric Ca I $\lambda 1083.9$ nm line for granulation, penumbra, and umbra are shown as solid lines in the colors green, blue, and red, respectively. Stokes QUV profiles for umbra and granulation were shifted by -0.01 and $+0.01$ for better visualization. Stokes UV profiles for the umbra are scaled down by a factor of 2 and 4, respectively, to fit in the displayed range. The SIR profiles are shown in the same color-code but as dashed lines.

The foremost reason to perform two-component inversions was to achieve better fits for double-lobe Stokes V profiles (see blue curve in Fig. 1). Another motivation was to infer additional physical parameters providing more insight into different regimes of magnetic fields and with respect to newly emerging magnetic flux.

2. Observations and Data Analysis

A two-week coordinated campaign was carried out in August 2015, which included observations from the GREGOR, the Vacuum Tower Telescope (VTT), Hinode, and the Interface Region Imaging Spectrograph (IRIS). We present one of the datasets observed on 2015 August 6, mainly focusing on the spectropolarimetric observations from the GREGOR Infrared Spectrograph (GRIS, Collados et al. 2012). The full Stokes polarimetric data were taken in the 1083.0 nm spectral range in an 1.8-nm-wide spectral window. This window covered the photospheric lines Si I $\lambda 1082.7$ nm and Ca I $\lambda 1083.9$ nm as well as the chromospheric He I $\lambda 1083.0$ nm triplet. The 300 scan steps with a step size of $0.144''$ and the image scale of $0.136'' \text{ pixel}^{-1}$ along the slit result in a field-of-view (FOV) of about $62'' \times 43''$, which takes about 30 min to record. The GRIS FOV covers the two trailing sunspots in the active region. In this work we mainly discuss the results for the near-infrared Ca I $\lambda 1083.9$ nm line. The Ca I line originates from the

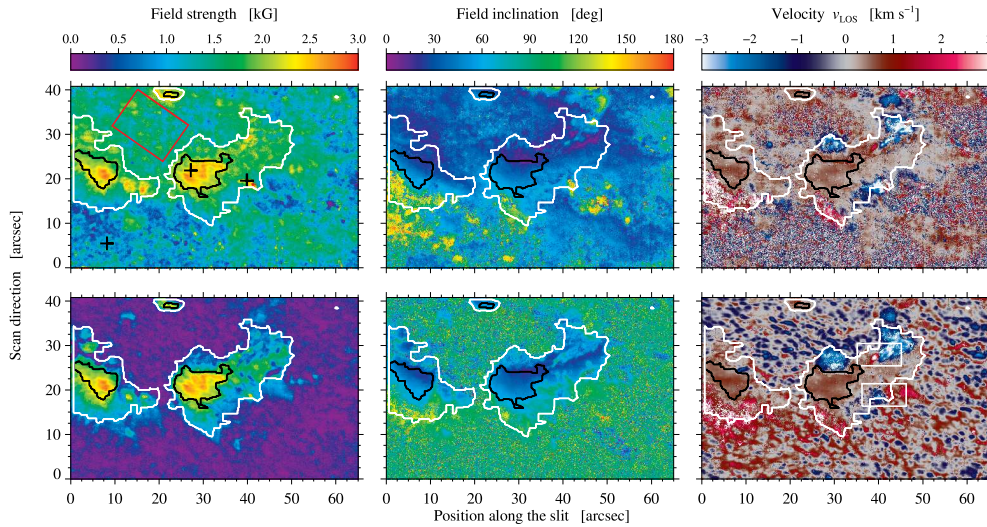


Figure 2. Maps of physical parameters derived with the SIR code for the Ca I line observed by GRIS at 09:24 UT on 2015 August 6: total magnetic field strength, magnetic field inclination, and Doppler velocity (*left to right*). The two-component inversions (*top and bottom*) were sorted according to the filling factor of both magnetic components, and the maps corresponding to filling factors larger 0.5 are depicted in the bottom panel. The black ‘+’ signs (*top-left*) mark the locations of the profiles shown in Fig. 1 and the red box mark the region with kilo-gauss fields. The white boxes (*bottom-right*) label regions with red and blueshifts in close vicinity.

transition between the $4p^3P_2$ and the $3d^3P_2$ levels, and is magnetic sensitive with a Landé factor $g_{\text{eff}} = 1.5$.

The basic calibration of the data was carried out on-site using the GRIS pipeline (Collados 1999). A careful wavelength calibration was performed by comparing the observed profiles with a near-infrared atlas profile obtained with the Fourier Transform Spectrometer (FTS) of the McMath-Pierce solar telescope at the Kitt Peak National Observatory (Wallace et al. 1996). We inverted calibrated GRIS spectra with the Stokes Inversions based on Response functions (SIR) code developed by Ruiz Cobo & del Toro Iniesta (1992). The starting model is a two-component model, which covers the optical depth range of $-4.4 \leq \log \tau \leq +1.0$. We opted for the two-component model to improve the fits of complex Stokes- V profiles. Examples of the SIR fits in umbra, penumbra, and quiet Sun are shown in Fig. 1.

3. Results and Discussions

Three days after emergence active region NOAA 12396 was still evolving at the time of GREGOR observations on 2015 August 6. The SDO/HMI continuum images and magnetograms (not shown here) allowed us insight into the temporal evolution of the region. They revealed ongoing changes in the appearance of the active region’s trailing part, especially concerning the evolution of sunspot penumbrae. Four hours before the GRIS observations the trailing part consisted of three negative polarity sunspots with two sunspots in the south with partial penumbra and the one in the north without

penumbra. In addition, many mixed polarity features were present between the leading and the trailing part. At the time of GRIS observations and few hours after we noticed that a full penumbra is prevented from forming in regions of ongoing flux emergence (see Schlichenmaier et al. 2010).

Full Stokes polarimetry from GRIS provided the photospheric and chromospheric line-core intensities, LOS velocities, and magnetic field information for the complex active region. Here, we focus on results obtained from the photospheric Ca I line. The magnetic field information was extracted by conducting a two-component inversion with SIR for the Ca I line. Two-component inversions were carried out because of the inability of one-component inversions to fit the double lobes in some of the V -profiles (see Verma et al. 2016). In addition to magnetic field strength the inversions provided the line-of-sight (LOS) velocities and magnetic field inclination (see Fig. 2). We displayed the maps based on the filling factor of both magnetic components. The maps corresponding to a filling factor larger than 0.5 are less noisy and depict the properties of features like sunspot umbrae well. These inversions were able to provide the reasonably good estimate of the magnetic field strength with about 2 kG in the umbra and with low field inclination. The most conspicuous features in the LOS velocities map were the red and blueshifts in close proximity near the penumbra of the right spot (see white boxes in Fig. 2). Matching these location with the HMI magnetograms, we deduced that these flows likely belong to regions with flux emergence. In the magnetic-field strength maps for low filling factors we found kilo-Gauss patches in the area between trailing and leading spot, i.e., the region with continuous flux emergence (e.g., red box in Fig. 2). These kilo-Gauss patches were not visible in the maps based on one-component inversions. In addition, the flux emergence in these region seems to inhibit the formation of penumbra in the sunspot, which never developed a stable and regular penumbra enveloping the whole sunspot. More recently Romano et al. (2013) reported a similar scenario where flux emergence hindered the formation of a stable penumbra.

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References

- Collados, M. 1999, in ASP Conf. Ser., Vol. 184, Third Advances in Solar Physics Euroconference: Magnetic Fields and Oscillations, eds. B. Schmieder, A. Hofmann, & J. Staude (San Francisco: ASP), 3
- Collados, M., López, R., Páez, E., et al. 2012, AN, 333, 872
- Romano, P., Frasca, D., Guglielmino, S. L., et al. 2013, ApJ, 771, L3
- Ruiz Cobo, B., & del Toro Iniesta, J. C. 1992, ApJ, 398, 375
- Schlichenmaier, R., Rezaei, R., Bello González, N., & Waldmann, T. A. 2010, A&A, 512, L1
- Verma, M., Denker, C., Böhm, F., et al. 2016, AN, 337, 1090
- Wallace, L., Livingston, W., Hinkle, K., & Bernath, P. 1996, ApJS, 106, 165