Sunspot model atmosphere from inversion of Stokes profiles

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ABSTRACT

Sunspots are prominent manifestations of the solar cycle and provide key constraints for understanding its operation. In addition, knowing the internal structure of sunspots allows us to gain insights on the energy transport in strong magnetic fields and, thus, on the processes inside the convection zone, where solar magnetic fields are generated and amplified before emerging at the surface on various scales. Here, we present results of a spectropolarimetric analysis of a sunspot observed during the declining phase of the solar cycle 23.

By inversion of full Stokes spectra observed in several spectral regions in the optical at the THEMIS facility we infer the height dependence of physical quantities such as the temperature, LOS velocity and magnetic field for different sunspot regions. The simultaneous inversion of all Stokes parameters of atomic (Fe I 5250.2 Å and 5250.6 Å) and highly temperature sensitive molecular (TiO 7055 Å and MgH 5200 Å) lines, formed in higher layers, allow us to extend and improve a sunspot model atmosphere.

OBSERVATIONS & INVERSIONS

The Stokes profiles obtained at the THEMIS facility (see Afram et al. 2006 and Arnaud et al. 2006) were inverted for each pixel independently employing the code SPINOR (Frutiger et al. 2000 and Berdyugina et al. 2003). This code assumes LTE conditions and solves the Unno-Rachkovsky radiative transfer equations using response functions.

Starting from an initial guess model the Stokes profiles are fitted iteratively to the observational data varying the atmospheric quantities. Temperature and magnetic field strength are iterated as height dependend free parameters at the five reference points log τ_{500nm} = -4, -3, -2, -1 and 0. In addition to the two magnetically sensitive Fe I lines at 5250.2 Å and 5250.6 Å different other atomic lines as well as features of TiO (7055 Å) and MgH (5200 Å) are present in our data. All lines were inverted simultaneously.

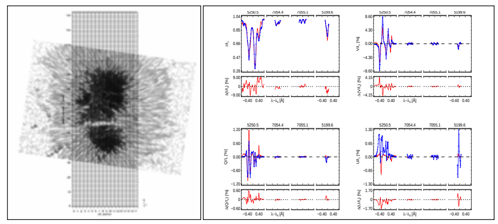

Figure 1: Left: An image of the observed sunspot NOAA 10667. The resolution and position of our data is indicated by the grid. The top and right hand side scales give the size of the sunspot which is ca. 15 x 25 arcsec. For each pixel a full Stokes profile is available. **Right:** The fit of a typical set of Stokes profiles is presented here for one umbral pixel (7, 53). The red solid line is observational data, the blue line is the synthetic best fit profile found by inversion. In Stokes Q and U the correct angle chi is determined.

RESULTS

The resulting sunspot atmosphere consists of one photospheric component, a standard quiet sun atmosphere responsible for straylight, and two magnetic components. The overall magnetic filling factor is about 0.92 (core umbra) splitted almost equally between the two magnetic components. A second magnetic component with a steep temperature gradient, believed to account for unresolved umbral structures, is unavoidable for best fit results. In general, known height dependencies of the magnetic field strength and the temperature are observed in the magnetic components. The temperature of the core umbra is around 3550 K, it bears an average magnetic field strength of around 3 kG.

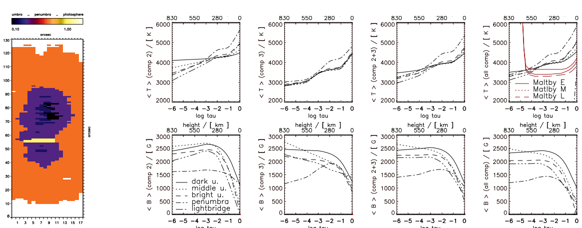

Figure 2: According to the map on the left, averages were build for different regions of the sunspot. The average temperature (upper row) and the average magnetic field (second row) are plotted over log τ_{500nm}. The columns show (from left to right) the first magnetic component, the second magnetic component, the combined magnetic component and the total combined atmosphere.

Within the chosen spectral range atomic lines constrain the inversion in deeper and hotter regions whereas molecules are present in higher, cooler layers of the photosphere. For the temperature of the total atmosphere other models of core umbra (Maltby 1968) are given as reference (Figure 2, above). The discrepancy between the models at very low log τ values is due to the lack of lines probing this very high layers. For two regions (dark core umbra and lightbridge) the stratifications of the temperature and the magentic field strength of single pixels are given below in Figure 3. From the experience with the inversions it can be concluded that molecular lines indeed constrain a model atmosphere. A detailed discussion of this sunspot model atmosphere is in preparation.

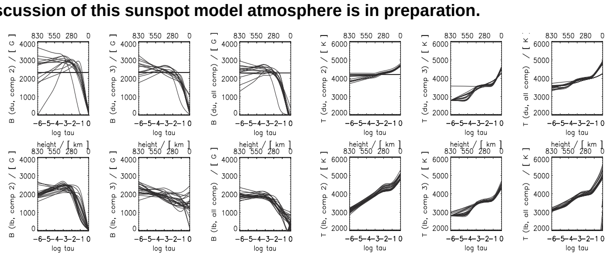

Figure 3: The magnetic field strength (first three columns) and the temperature stratification (last three columns) for the pixels from two regions of the sunspot under consideration. In the upper row pixels from the darkest part of the umbra are presented, the row below shows pixels from the lightbridge region.

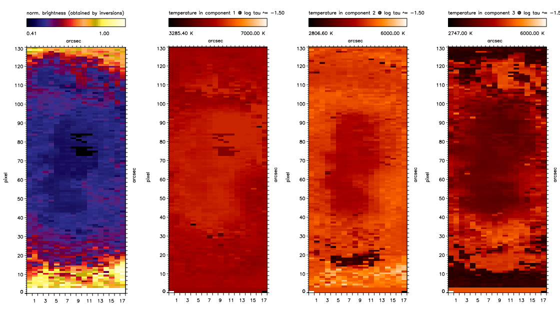

Figure 4: On the left the result of the inversion is presented as brightness map of the total atmosphere (combination of all components). Each component's temperature is shown by the three maps on the right; ach at a depth of log τ_{500nm}= - 1.5.

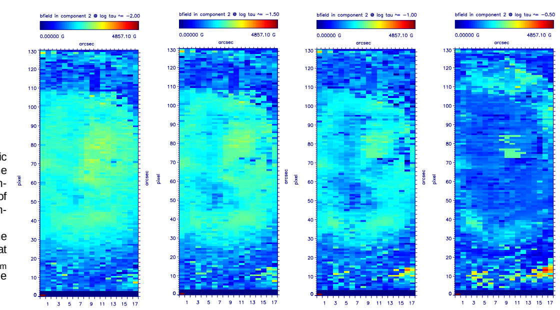

Figure 5: Magnetic field strength of the total magnetic component (combination of the two magnetic components).
From left to right the horizontal cuts at different log τ_{500nm} values approach the solar surface.

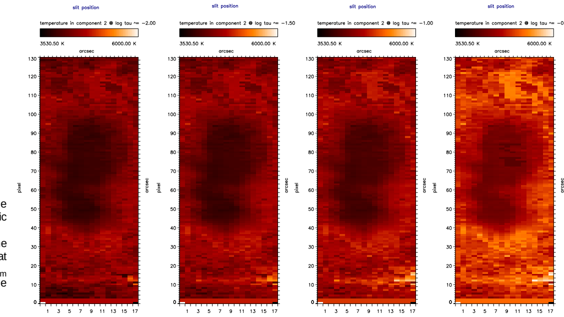

Figure 6: Temperature of the total magnetic com-ponent.
From left to right the horizontal cuts at different log τ_{500nm} values approach the solar surface.

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