High Resolution Imaging Spectroscopy of Sunspots

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Abstract.

We present high resolution imaging spectroscopy measurements of sunspots observed at the NSO/Dunn Solar Telescope using Adaptive Optics, and a cascaded, tunable dual-Fabry Perot imaging interferometer system. Using this instrument we have observed sunspots in the FeI 5576Å spectral line, and simultaneous G-Band images. We present thermal and velocity measurements of two sunspots: NOAA 9268 observed on December 19, 2000, and NOAA 9451 observed on May 10, 2001. We present intial results from fitting intensity profiles using the Stokes Inversion based on Response Functions (SIR).

1. Introduction

Sunspots represent a significant aggregation of magnetic fields in the presence of convection. An understanding of the structure of sunspots will help us follow the nature of balance between magnetic and convective forces in the solar photosphere. In this paper, we will extend some of the previous work by Balasubramaniam (2002). In addition, we will compare the measured thermal and velocity structure from bisector measurements to actual fitting of profiles using Stokes Inversion based on Response Functions (SIR; Ruiz Cobo & del Toro Iniesta 1992, 1994) for the intensity profiles.

2. Instrument and Observations

Data used in these observations were obtained with the National Solar Observatory/Dunn Solar Telescope at Sacramento Peak, Sunspot, NM. A dual-Fabry Perot (FP) etalon system was used to make the measurements. The dual-FP system is used to obtain high-resolution imaging spectra sequentially across a spectral line. The instrumental details are described in Balasubramaniam (2002).
Figure 1. Top panel: Intensity (top-left) and LOS velocity (top-right) of NOAA 9268 (2000 December 19). The velocity is scaled between ±1.5 km s\(^{-1}\). Bottom panel: Intensity (top-left) and LOS velocity (top-right) of NOAA 9451 (2001 May 10). The velocity is scaled between ±0.5 km s\(^{-1}\). For both panels, North is to the top and West is to the left.

The data included in this paper were derived from observations of active region NOAA 9268 (2000 December 19, S18E1 at 16:08:05 UT), and NOAA 9451 (2001 May 10, S21E13 at 16:32:23 UT).

Figure 1 shows the measurements for NOAA 9268 (top panel) and the measurements for NOAA 9451 (bottom panel). We obtained sequential spectral scans about the non-Zeeman sensitive spectral line FeI 5576.09Å, for each of these two sunspots. Each spectral scan consisted of 18 (20 mÅ steps/image) images for NOAA 9268 and 17 images for NOAA 9451. Simultaneous G-Band and H\(\alpha\) images were obtained at every exposure.
Figure 2. Sampling of the nearby quiet-sun (Fig. 1; bottom left; NOAA 9451) about the FeI 5576.09 Å spectral line, when compared with the quiet-sun solar disk-center atlas. The atlas and the data are correspondingly scaled such that the continuum is at 100.

3. Data Analysis and Discussion

The measured spectral, G-band and Hα images were corrected for the CCD camera dark-current noise and the instrumental flat-fielding effects. The mean value of the quiet-sun in the G-band images were used as a measure of the fluctuating light-level. The changing light level is due to changing elevation of the sun during the course of observations upon which the fluctuations due to seeing, is superposed. The intensity values in the spectral images were normalized to the light level. In Balasubramaniam (2002), figure 4 therein shows the comparison of a solar disk-center spectral atlas (Delbouille, Roland & Neven 1973) with the quiet-sun profile, in a region about NOAA 9268. In Fig. 2, we depict the the measured spectral points in the quiet-sun spectrum, in comparison with the atlas for NOAA 9451.

Since the quality of image seeing measured at any temporal point varies due to a fluctuating terrestrial atmosphere, we used the nearby quiet-sun granular contrast for each image to identify the quality of seeing. Hence, we retained only those spectral image sequences where the root mean square granular contrast was higher than 0.05 and the fluctuations in the granular contrast did not exceed 3% of the mean, within any given sequence. A contrast level of 0.05 in the sequence implies an excellent image (see figure 3, in Balasubramaniam 2002).

3.1. Doppler Measures

Using the spectral line measured at each spatial point, we measured the center-of-gravity (COG) wavelength, $\lambda_{cog}$. The mean COG wavelength about a nearby
quiet-sun area was used as a reference wavelength ($\lambda_{ref}$) to derive the Doppler shifts. $V_{Dop} = \frac{\lambda_{obs} - \lambda_{ref}}{\lambda_{ref}} \times c$, where $c$ is the velocity of light. In Fig. 1 (right panel) we show the measured Doppler shifts about the FeI 5576.09Å line. The top-right panel shows the mean Doppler shifts derived from nine spectral scans and the bottom-right panel shows the mean Doppler shifts derived from three spectral scans. Both sunspots clearly show the Evershed effect. In the bottom right panel (NOAA 9451) of Fig. 1, we clearly see that the light bridges across the sunspot shows opposite flows, and similar in sense to the sign of the Evershed flow. Measurement of light-bridge velocities and their interpretation as being due to convective motions have been explained in detail by Leka (1997), Rimmiele (1997) and Hirzberger et al. (2002). The light-bridges are oriented significantly in the E-W direction and that velocities appear opposite in sense on either side of the light-bridge similar to the Evershed flow, we wonder if light-bridge convection is modulated by a mechanism similar to the Evershed flow.

3.2. Flow-less Intensities and Radiation Temperature

![Figure 3](image-url) An image of the thermal span for NOAA 9451 (left panel) and a cross-sectional plot of the thermal span (right-panel) about the sunspot as marked by the fiduciary line. The temperature scale on the vertical axis is in K.

The intensities of emergent radiation in a non-Zeeman spectral line are influenced by both the Doppler effect and the thermodynamics of the spectral line forming region. The spatial variation spectral line properties in a sunspot are influenced by both Doppler and thermal effects. We create a flow-less map, where the gross Doppler shift influences of the spectral line are minimized. We derive a flow-less spectral line map of sunspot FeI 5576.09 Å spectra by shifting
the wavelength scale for each of the spatial point by the corresponding $\lambda_{\text{cog}}$, and interpolating the spectral line on a uniform (20 mA) spectral grid, such that $I_{\lambda_{\text{new}}} = I_{\lambda} - \lambda_{\text{cog}}$. For a detailed discussion see Balasubramaniam (2002).

We have converted the flow-less intensities at each depth in the spectral line to a radiation temperature. Using a VAL-C model and under conditions of LTE the continuum intensity for a mean photosphere is $3.85 \times 10^{-8}$ J m$^{-2}$ s$^{-1}$ Hz$^{-1}$ sr$^{-1}$ (Courtesy H. Uitenbroek, private communication). Using this value, we have converted the intensity (L/C ratio, $I_{\lambda}$) at each point in the spectral line into a radiation temperature $T_{\text{rad}}$.

Using the thermal maps, we derive the thermal span of radiation temperatures across the sunspot. The thermal span is the temperature difference between the maximum and minimum temperatures spanning the spectral line, from the continuum to the core. Such a thermal span image, and a cross sectional plot of the thermal span are shown in Fig. 3 for NOAA 9451. The thermal span for NOAA 9268 (2002 December 19) is shown in a figure in Balasubramaniam (2002).

The thermal span of temperatures within the umbra is lowest, pointing out a rather stable umbra. The temperature differences within the height of the formation of the FeI 5576 spectral line (100 - 400 km above $\tau = 1$ layer) is about 700 K for the umbra, whereas the thermal span in the penumbra and photosphere ranges in the values between 1200 and 1400 K. Comparing these with the measurements of NOAA 9268 (Balasubramaniam 2002) we find that the span of temperatures for the umbra is somewhat similar in the umbra, whereas it is lower by about 150-200 K in the penumbra and the photosphere. Perhaps the thermal span of temperatures in the umbra, relative to the neighboring penumbra and photosphere holds clues to the longevity and the evolutionary life-time of a sunspot.

3.3. Bisector Velocities

Measures of bisector Doppler shifts along the depth of a spectral line indicate the relationship between the dynamics and the height of formation of a spectral line. To measure the bisectors we derived 20-equispaced intensities between the spectral line core and the continuum (see Balasubramaniam 2002, for details). In Fig. 4 we depict the bisector velocities for the sunspot NOAA 9415. We note that the bisector velocities are similar to those of sunspot NOAA 9268. The bisectors velocities in the umbra (grid points [3,5], [4,5], [5,5]) reveal a sharp changing structure with height, while the bisectors in the penumbra and the photosphere are far more gradual.

3.4. SIR Inversion

A complete non-linear least square inversion for the intensity spectra, similar to Westendorp Plaza et al. (2001) or del Toro Iniesta, Bellot Rubio & Collados (2001) would be necessary to quantitatively resolve these temperature structures at particular depths.

We have begun to experiment with the SIR inversion process Ruiz Cobo, & del Toro Iniesta (1992, 1994) for NOAA 9268. We refer the reader to those papers on the details of the SIR inversion process. Using a 4-cycle inversion process and starting with the HSRA model atmosphere, we systematically let
Figure 4. A sample cross-section of the bisector velocities across a sunspot. The asterisk points on the sunspot figure (left) show the locations where the individual bisectors (right) are identified in the corresponding 64 positions on the spot. The box at the umbra and photospheric locations cover a region of 3-square arcseconds.

the number of nodes for the inversion process change by 1, 2, 5, and 9 levels, for continuity. Perturbing the HSRA model atmosphere, the parameters we derived to fit to the spectral line were temperature, electron pressure micro-turbulent velocity and the macro-velocity as a function of the optical depth.

In Fig. 5 we show the model parameters as a function of the optical depth for temperature, electron pressure, micro-turbulent and macro-turbulent velocities. The curve with the most extreme variations is the umbral and the two similar looking curves are for the penumbra (dotted) and photosphere (dot-dashed). The corresponding error bars, a product of the SIR, are also plotted. Since the depth of formation for FeI 5576.01 is realistic between optical depths (log\(_\tau\) values) of -2 to 1 perhaps these parameters are valid only for those optical depths. A further investigation of comparing the measured bisector velocities and bisector temperatures versus those resulting from the SIR models is warranted.

4. Concluding Remarks

We have now tested the measurement of flow-less intensity maps, Doppler velocities, bisector velocities consistently on two sunspots and the results appear similar. In addition we note the presence of convective rolls in light bridges. We also note that our first applications of SIR inversion on the intensity profiles of
FeI 5576.01 gives good results. Our next goal is to verify the limited interpretational usefulness of these results in building future models of sunspots.

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References

Figure 5. Model plots of temperature, electron pressure, micro-turbulent and macro-turbulent velocities for a sample umbra (extremal variations), penumbra (dotted lines) and photosphere (dotted-dashed lines) The error bars retrieved by the SIR are indicated.