The Observed MnI 539.47 nm Spectral Line in Three Sunspots of the NOAA 0431 Complex Active Region

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Abstract. The spectra of the MnI 539.47 nm spectral line was observed in three sunspots of the NOAA 0431 active region on a three successive days. The observation was made with the horizontal solar spectrograph at the Heliophysical Observatory of Debrecen, Hungary. The spectra of each sunspot were cropped into several boxes perpendicular to the dispersion axis in such a way to cover their umbra, penumbra and surroundings. The cropped spectra were thereafter reduced and the manganese spectral line parameters (equivalent width, central depth and full width at half of the maximum intensity) were measured. Finally, the variation of the spectral line parameters along the spectrograph slit were determined and analyzed.

1. General Introduction

It is an observational fact that the MnI 539.47 nm photospheric spectral line profile parameters (equivalent width, central depth and full width at half of the maximum intensity; hereafter EW, CD and FWHM respectively), when the integrated solar light is observed, shows relatively large variation in time. Time series taken at the Kitt Peak Observatory, Arizona, shows that the amplitude of the EW and CD variation during the solar activity cycle is about 2% (Livingston 1992; Vince & Erkapic 1998). Beside, Livingston (1992) showed a very high correlation between EW and CaII K index. Since then, the MnI spectral line and its strange behavior (i.e. high cyclic variation of its parameters despite the fact that the manganese atoms are formed in the quite photosphere) is a matter of investigation.

In order to give a reasonable explanation to this observational fact, several hypotheses were introduced and verified in the past. At first, it was supposed that the high amplitude of variation of the MnI spectral line parameters could be due to temperature variation in the photosphere where the Mn atoms are formed. In order to verify this hypothesis, the temperature sensitivity of the MnI spectral line was determined. First, it was done theoretically calculating the relative changes of EW, CD and FWHM by variation of the temperature gradient (Erkapic & Vince 1998). It was demonstrated that, in comparison to other photospheric spectral lines, the MnI 539.47 nm spectral line is much more sensitive to temperature changes. In order to verify this result experimentally, several solar-like stars with different effective temperature was observed and, using a stated calibration curves (i.e. the manganese spectral line parameters versus effective temperature), the temperature sensitivity of the MnI spectral line was determined (Vince et al. 1998; Vince & Vince 2001). Again, it was
shown that the MnI spectral line parameters are highly temperature sensitive but the obtained results differed from the theoretically obtained one. The temperature sensitivity determination was revised including the hyperfine structure of the manganese spectral line but the discrepancy remained (Vince & Vince 2002). Supposing that it is because the stars (used for temperature sensitivity determination) have different metallicity, rotational and macroturbulent velocity, correction for these parameters was made (Vince 2003). While the correction of the MnI parameters for metallicity improved the results, corrections for other parameters turned out to be impossible. The spectral resolution and the SNR of the stellar spectra were not high enough to determine some stellar parameters which are not listed in the catalogs. On balance, both theory and experiment (regardless to quantitative different results), proves that the temperature sensitivity of the MnI 539.47 nm spectral line is not enough to explain the large variation of its parameters during the solar activity cycle.

The following hypothesis was based on the idea that the MnI spectral line could be influenced by chromospheric plage and that the plage-area coverage variation during the solar activity cycle might explain the MnI spectral line behavior (Vince & Erkapic 1998). Comparing the MnI spectral line calculated in average quite region and plages, it was shown that the plage-area coverage of about 10% in the solar activity maximum is necessary for this. This value is much bigger than the observed one. As an another test, the magnetic sensitivity of the MnI spectral line parameters were determined by observing this line in plages of different magnetic field intensity (Vince et al. 2000). Assuming an average magnetic field intensity of 500 Gauss in plage region, the 2% amplitude variation requires a plage-area coverage of about 3% in the solar maximum. This also exceed the observed value. In all, this idea does not provide a reasonable explanation for the MnI line problem.

Recently, using multi-line/multi-species NLTE modeling it has been shown that the MnI 539.47 nm photospheric spectral line might be optically pumped by photons which derives from the MgII 279.5 nm (MgII k) chromospheric spectral line (Doyle et al. 2001). In more detail, the MnI spectral line has strong
interaction with the MnII k chromospherich spectral lines since they have common energy level. This hypothesis provides an interesting qualitative solution for the MnI spectral line problem but does not give any quantitative answer. In other words, what is the effect of optical pumping on the MnI spectral line parameters is not known.

It is natural to assume that beside the mentioned factors, some others may also contribute to the manganese spectral line parameters variation in time. To get a whole picture, it is necessary to investigate all of them. In this paper, the influence of the sunspot on manganese spectral line profile parameters is investigated. The observed spectrum of three largest sunspots of the very complex active region NOAA 0431 taken on three successive days is processed and analyzed.

In the first section, the instruments which were used for observation are described. Thereafter, the data reduction and measurement of the MnI parameters are explained. This is followed by discussion of the obtained results and conclusion.

2. Instruments

The observations were carried out with the Lyot coronagraph (with displaced artificial “moon”) and horizontal spectrograph at the Heliophysical Observatory of Debrecen, Hungary. Diameter of the telescope’s objective is 53 cm. Its focal length at $\lambda = 550$ nm is about 8 m. In order to increase the solar image size at the entrance slit of the spectrograph, an additional optics were mounted giving effective focal length of about 12 m and providing about 12 cm image of the Sun (more about the Lyot coronagraph can be found in Gnevyshev, Nikolsky, & Sazanov (1967). The spectrograph is Czerny-Turner type. Collimator and camera mirror are 36 cm and 42 cm in diameter respectively. Their focal length is 800 cm. The spectrograph is supplied with 25 x 23 cm grating of 600 grooves per millimeter. The observations were made in the fourth spectral order isolated by two broadband glass filters; ZhS17 and SZhS23. With 50 $\mu$m wide entrance slit we obtained about 0.9 pm/px (30 pm/mm) dispersion. The fringing patterns on the CCD image were eliminated by tilting the CCD camera by about 5 degrees.

3. Observations and Reductions

The observations were made on three successive days, August 16, 17 and 18, 2003. The target were three large sunspots in the NOAA 0431 prominent active region near the solar limb. Position of this active region on 18$^{th}$ August can be seen on the left side image of Figure 1.

On the right side of Figure 1., the white-light (top) and CaII (bottom) images of the active region for all three days are given (the images were taken from the Big Bear Solar Observatory observational data archive; http://www.bbso.njit.edu). The arrow on the enlarged white-light image (last image on the right) symbolize the entrance slit of the spectrograph which was adjusted to cover about 120$''$x 0.9$''$ of the solar disc. The observed sunspots are marked by b, c and d.
Figure 2 illustrates the distribution of the sunspots and pores in the NOAA 0431 active region for all three days (the images were taken from the Crimean Astrophysical Observatory observational data archive, http://www.crao.crimea.ua). The polarity of the sunspots and their magnetic field intensity ($B_s$) are designated, respectively, with letters (S and N) and numbers. The size of the investigated sunspots (b, c and d) and their mean magnetic field intensity, as it is evident from the figure, decrease in time. The mean magnetic field intensity in the sunspots for all three days are summarized in Table 1.

Table 1. The average magnetic field intensity in all three sunspots.

<table>
<thead>
<tr>
<th>Days</th>
<th>Sunspot b</th>
<th>Sunspot c</th>
<th>Sunspot d</th>
</tr>
</thead>
<tbody>
<tr>
<td>August 16</td>
<td>2.2</td>
<td>2.2</td>
<td>2.4</td>
</tr>
<tr>
<td>August 17</td>
<td>2.0</td>
<td>2.1</td>
<td>2.2</td>
</tr>
<tr>
<td>August 18</td>
<td>1.9</td>
<td>1.8</td>
<td>1.7</td>
</tr>
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</table>

Although the solar image on the entrance slit of the spectrograph was relatively small (12.6 cm in diameter), during the observation we were trying to observe the sunspots in the same position. For each sunspot we made five spectra per day (45 spectra all together). Spectra were combined (averaged) using the MaxImDL program package (George et al. 1993). Using the Analyst program package (Malkov 2003), the combined spectra were divided into five pixels wide boxes cropped perpendicularly to the dispersion axis in such a way to cover the whole sunspot and its surrounding. Figure 3, illustrates the relative intensity variation along the entrance slit of the spectrograph made in the MnI spectral line. While the deepest minimums belongs to sunspots b, c and d respectively, others are caused by small sunspots and pores in their vicinity. The vertical straight lines corresponds to the center of the boxes. The caps on the top/bottom represents the width of the boxes. All boxes are designated with numbers except one ("max") which denotes the box cropped at the position of the spectra with the maximum relative intensity. We believe that this box belongs to plage region with maximum intensity along the slit but because of
complexity of the active region it is hard to tell whether it is a pure plage area. The prominent global increase of the relative intensity from left to right is not due to darkening effect toward the solar limb since the orientation of the entrance slit was just opposite. It is probably caused by intensity distribution in the plage region.

Figure 3. The relative intensity variation along the spectrograph entrance slit together with the cropped boxes.

4. Discussion

Using the Analyst program package, one-dimensional spectra were extracted from the boxes. Thereafter they were normalized to the local continuum and calibrated to the wavelength. Finally, the MnI 539.47 nm spectral line parameters were measured.

Figure 4, illustrates the manganese spectral line parameters variation perpendicularly to the dispersion axis. The data are normalized to the “max” value. The relative variation of these parameters (in percentage) on all three days for the sunspots are summarized in Table 2. As it can be seen, the relative change of EW and CD for sunspots c and d, decrease in time. Sunspot b, shows different behavior, i.e. EW vary and CD increase in time. Since the size of the sunspots and their mean magnetic field intensity shows similar trend in time (both decrease; see Figure 2.), it is expected to have similar behavior for the spectral line parameters of all sunspots. The complex struture of the sunspot b may be
the reason for not having the above said behaviour. The future discussion will therefore be restricted to sunspots c and d.

As it is known, decrease of the magnetic field intensity in sunspot, leads to the increase of the effective temperature \( T_{\text{eff}} \). From earlier studies of the Mn I spectral line, we know that its parameters are sensitive to \( T_{\text{eff}} \), i.e. all parameters decrease with increasing \( T_{\text{eff}} \) (Vince & Vince 2001; Vince et al. 2000). Behavior of the Mn I's EW and CD, as it is presented in Table 2, is in agreement with this studies. On the other hand, the Mn I parameters measured in the solar flux anti-correlate with Wolf’s sunspot number and other solar activity indices. Thus, we may conclude that, despite the fact that the Mn I spectral line parameters are more influenced by temperature changes when sunspots are observed individually, the net effect of sunspots is not the main driver of the Mn I line variation in solar flux during the solar activity cycle.

Concerning the third spectral line parameter (FWHM), according to Table 2., it does not change (or change slightly in time). This is in agreement with the mentioned studies of the Mn I spectral line temperature sensitivity.

5. Conclusion

In this study, the influence of different sunspots of the NOAA 0431 complex active region on the Mn I 539.47 nm spectral line was investigated. Since the observations were made on three successive days, we were able to trace this
The MnI 539.47 nm Spectral Line in Sunspots

Table 2. Average magnetic field intensity in all three sunspots.

<table>
<thead>
<tr>
<th>Days</th>
<th>Sunspot b</th>
<th></th>
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<tr>
<td></td>
<td>EW CD FWHM</td>
<td>mÅ</td>
<td>EW CD FWHM</td>
<td>mÅ</td>
<td>EW CD FWHM</td>
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<tr>
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<td>21</td>
<td>16</td>
</tr>
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influence in time i.e. with different sunspot shapes/sizes and mean magnetic field intensity. It was found, that by decreasing the mean magnetic field intensity in the sunspots the MnI parameters decrease. It was also shown that the MnI line parameters are more influenced by temperature changes in sunspot but the net effect of the sunspot is not the main reason for the high amplitude variation of these parameters in solar flux spectrum during its activity cycle.

References

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