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THE Mn I 539.47 nm LINE VARIATION IN SOLAR ACTIVE REGIONS

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Abstract. It is a well-established fact that the Mn I 539.47 nm line exhibits significant cycle dependence similar to lines arising in the chromosphere which are affected by non-thermal heating in the chromospheric plages. Among these lines the case of the Mn I 539.47 nm line seems unique. It is of photospheric origin on the basis of theoretical calculations but its cyclic dependence hints at a chromospheric nature. The present work provides further evidence to both connections. The line exhibits asymmetry features and a center-to-limb variation as though influenced by the photospheric granulation. On the other hand an enhancement of the central intensity has been detected in a well identifiable Ca plage area. The line seems to be a promising candidate as an irradiance variation indicator.

1. Introduction

Activity-dependent chromospheric lines make significant contributions to the spectral irradiance variations of the Sun, especially outside of visible spectral regions. Some of these lines are subjects of regular observations (e.g., Ca II K line at 393 nm, Mg II lines at 280 nm, CN at 388 nm, etc.) and are constituents of irradiance models. Among these activity-sensitive spectral lines a fairly specific case is that of the spectral line Mn I 539.47 nm.

Livingston and Wallace (1987) published time series of several lines, including the Mn I 539.47 nm line between 1976 and 1985. The equivalent width and depth of this manganese line exhibited a definite cycle dependence. They also compared its behavior with the intensity of the central K3 dip of the Ca II K 393.3 nm line and found strong correlation indicating the chromospheric nature of this manganese line. This work was a part of a long-term project (Livingston, 1992) in which a systematic search has been conducted for cycle-dependent lines since 1974 by observing the Sun as a star. About 100 lines in 20 spectral windows were followed.

Cyclic behavior was detected for several lines. As is expected chromospheric lines show a strong cycle response, while photospheric lines vary only slightly with the single exception of the Mn I 539.47 nm line. Its equivalent width varied from about 78.6 mÅ at maximum to about 79.8 mÅ at the minimum of the solar activity cycle.

At the Belgrade Astronomical Observatory a long-term observational program was introduced in 1986 by using a solar spectrograph without imaging telescope, i.e. by observing the Sun as a star (Vince, Kubicela, and Arsenijevic, 1988). Since then, among other spectral lines, a great number of observations have been gathered about the Mn I 539.47 nm line and its unusually high degree of variation has been recognized and investigated (e.g., Vince and Erkapic, 1988). Supposing that such a high degree of variation could be due to a high temperature sensitivity of this spectral line, we investigated it theoretically (e.g., Erkapic and Vince, 1993; Vince and Vince, 2003) and experimentally by measuring its parameters from observed spectra of solar-like stars of different effective temperatures (e.g., Vince *et al.*, 1998; Vince and Vince, 2002, 2003; Vince, 2003). We concluded that solar effective temperature variation of about 1–1.5 K (during the activity cycle) is not sufficient to explain the variation of this line, although, its influence is not negligible, being about 10–20%.

It is widely accepted that the cyclic variation of a line implies a chromospheric origin. When observed in integrated sunlight the behavior of lines originating in chromospheric plages by non-thermal heating should reflect the rate of coverage of solar disk by plages. However, theoretical considerations indicate that this specific manganese line arises at the photospheric level. A comprehensive list of Fraunhofer line parameters is published by Gurtovenko and Kostyk (1989). They provide among other data the height of formation of the line center, which is 280 km, and of the line as a whole, which is 248 km. These are photospheric levels at which no activity-dependence is expected.

An interesting suggestion has been published by Doyle *et al.* (2001). They demonstrated that the cyclic variation of the Mn I 539.47 nm line parameters might be in great part due to the influence of the emission core of the Mg II k chromospheric line on the electron population of the ground energy level of the manganese atom. Using multi-line and multi-species NLTE calculations, they have shown that there is a link between Mn I 539.47 nm line sharing the same energy level as the Mn I 279.48 nm line in multiplet uv1, which has an interaction with the Mg II k line. When the core of Mg II k line is in strong emission, the ground level of the manganese atom is de-populated. Since the emission reversal in the core of the Mg II k line is enhanced in plage regions, the Mn I 539.47 nm line is weakened during solar activity maximum. Our observations (Vince *et al.*, 2000; Andriyenko, 2004) of the Mn I 539.47 nm line in plages and results of Malanushenko, Livingston, and Jones (2004) qualitatively support the results of these calculations. However, it has to be emphasized that for a quantitative explanation of the Mn I 539.47 nm line behavior, a complete NLTE spectral line formation modeling is necessary, also taking into account the hyper-fine components of this line.

It can be supposed that the variation of this line profile during the solar cycle is due to the combined effect of temperature variation and variation of plage region coverage. However, besides the influences exerted by these factors for the quantitative explanation of the Mn I 539.47 nm line profile variation with the solar activity cycle it is necessary to examine the influence of the sunspots too.

The earlier observations were carried out in integrated sunlight, in a “Sun as a star” approach. Further evidence can be provided by spatially resolved observations, in active regions (sunspots and plages), and in the center-to-limb variation of the quiet photosphere. The observations to be reported in the present paper were motivated by this idea.

2. Line Behavior in Active Regions

Our observations were carried out in 2001 and 2003 using the horizontal spectrograph (Gnevyshev, Nikolsky, and Sazanov, 1967) of the Debrecen Observatory. The solar image is formed at the coude focus by a telescope-refractor with an objective of 53 cm in diameter and about 12 m effective focal length. We had the opportunity to observe three active regions: NOAA 9563, NOAA 9575 and NOAA 0431.

The active region NOAA 9563 has been classified as a large beta–gamma sunspot group (BBSO Solar Activity Report). The big preceding spot of this active region was observed on the 6th of August 2001. Figure 1a shows a NSO white-light image of the solar disc on that day; an arrow indicates the position of the 50 μm wide spectrograph slit. The fourth spectral order was used with a dispersion of 8 mÅ/pixel. An SBIG ST-6 CCD camera detected the spectrum. Figure 1b shows

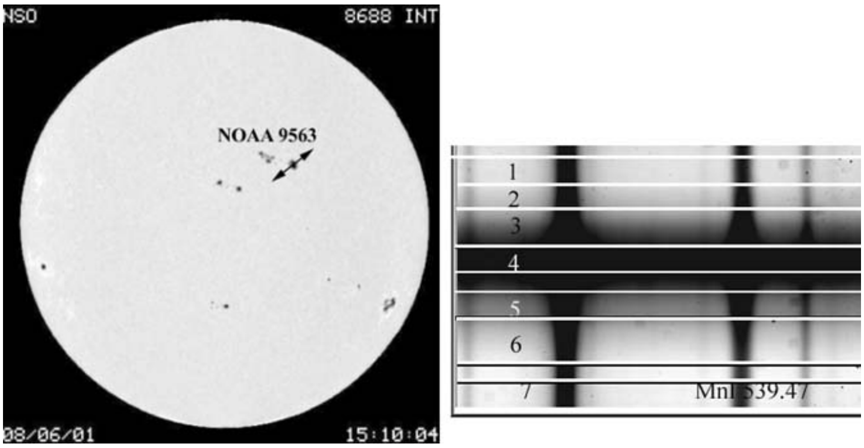

Figure 1. (a) NSO white-light image of the Sun on 6 August 2001, 15:10:04 UT (*left*). The *arrow* indicates the position of the slit across the spot of the NOAA AR9563. (b) CCD image of the spectrum with the Mn I 539.47 nm line and the centers of the measuring strips (*right*).

an image of the spectrum in about a 0.3-nm wide spectral window containing the Mn I 539.47 nm line.

The behavior of the line was analyzed by determining the line profiles in seven sections along the spectrograph entrance slit which were centered on the positions indicated in Figure 1b. These sections gave strips of different widths in the spectrum. The widths were chosen to minimize the impact of some CCD defects (frost specks or dust grains on the CCD window). Moreover, some parts of the CCD image were excluded from further reduction (for instance the part between 6 and 7 strips). In our case this was the only possibility to disclose the uneven background because the unavoidable fringe patterns cannot be eliminated by the standard flat-field procedure. We exploit the circumstance that the continuum does not change within 0.3 nm and the spectrum was corrected by fitting a curve to the observed continuum. By averaging the intensities perpendicularly to the dispersion one can minimize the distortion of the profile by small defects.

The central strip (4) belongs to the umbra; four strips (2, 3, 5, 6) belong to the penumbra and two (1 and 7) to the quiet photosphere or to the surrounding plage area (we were not able to separate plage and photospheric areas). By averaging along the slit a one-dimensional spectrum was obtained for each strip. Normalization to local continuum and wavelength calibration were performed for these spectra. The relevant line profiles are depicted in Figure 2b. Their position-dependence is remarkable.

To illustrate the variability of the line, three parameters of spectral line profiles are determined: the equivalent width (EW), full width at half maximum (FWHM) and central depth (r), for these seven positions. The obtained values are normalized to those detected at position 1 (Figure 3). All three parameters increase by proceeding from the photosphere or the plage area to the umbra. The FWHM and r increase by about 30% and the EW by about 70%.

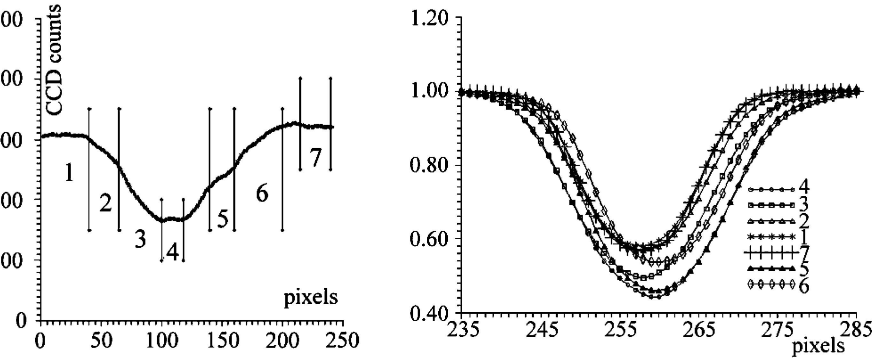

Figure 2. (a) The relative intensity variation along the spectrograph slit and the positions of seven strips that divide the spectrum in that direction (*left*), (b) line profiles derived from the strips (*right*).

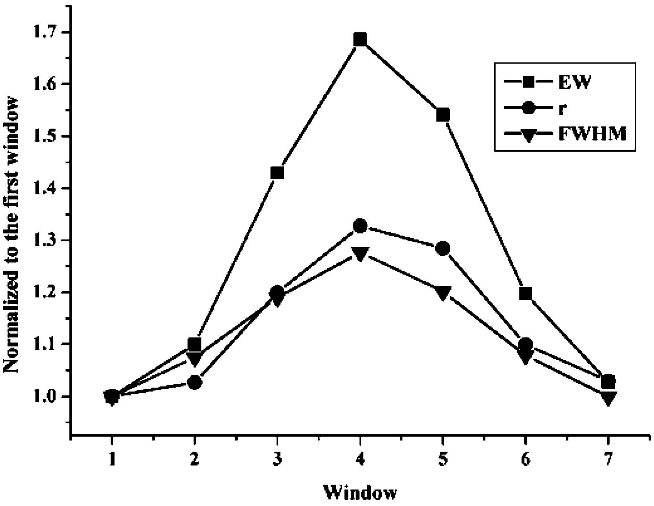

Figure 3. The behavior of line depth, half width and equivalent width of the manganese line across the sunspot of the active region NOAA 9563.

The next observed object was a single spot of NOAA 9575 on 14 August 2001. This active region has been classified as a beta region with large leading sunspot (BBSO Solar Activity Report). The MDI white-light full disc image is shown in Figure 4a; a bar indicates the position of the slit. Figure 4b shows the Ca II K image of the Big Bear Solar Observatory. It is evident from the comparison of the two

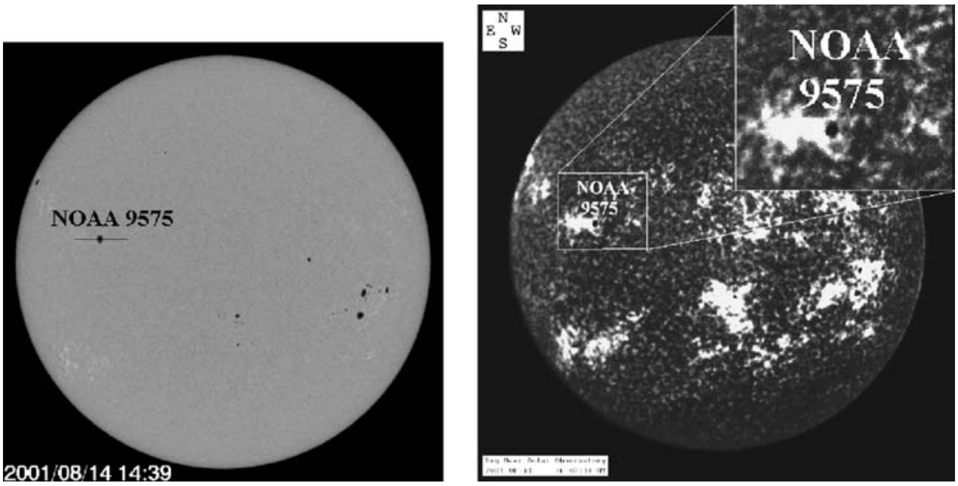

Figure 4. (a) The MDI white-light image of the Sun on 14 August 2001 with the indication of the spectrograph slit position across the spot of NOAA AR9575 (*left*), (b) the Ca II K image (Big Bear) of the same day (*right*).

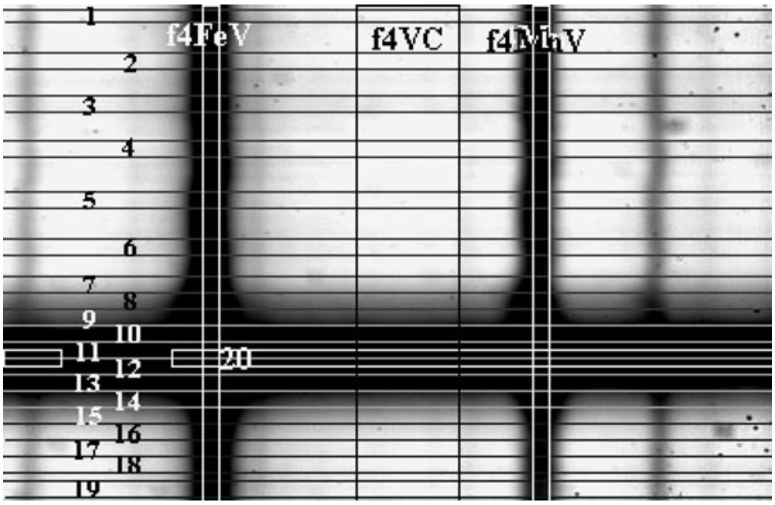

Figure 5. The positions of the measuring strips across the spectrum.

images that the slit crossed the photosphere, the umbra and the chromospheric plage to the east of the spot. So these records yield an opportunity for a direct comparison of the line profiles in the quiet photosphere, plage and sunspot. All observing conditions were the same as before.

This time the spectrum was crossed by 20 measuring strips parallel to the dispersion (Figure 5), namely, 1–6 strips: quiet photosphere; 7–9, 14, 15: penumbra; 10–13 and 20: umbra and 16–19: plage. From each strip a one-dimensional spectrum was obtained by averaging along the slit. The spectra were normalized with respect to the local continuum and calibrated in wavelength. In order to compare their behavior the FWHM, EW and *r* (central depth) have been computed from the profiles of each strip. They are depicted in Figure 6, normalized to the values of strip 1 (belonging to the quiet photosphere).

The half width of the line increases in the sunspot but its value is the same in the photosphere and the plage. This insensitivity of half width to change from photospheric to plage region is probably due to the relatively large broadening of the spectral line profile under the influence of its hyperfine components, which makes this line parameter less sensitive to environment changes, as was demonstrated in the case of magnetic field by Vitas, Vince, and Vince (2002).

The most important feature of the figure, however, is that the central depth decreases in the plage with respect to the photosphere. This is the same behavior that is exhibited by the core of strong chromospheric lines, which also have higher intensities in plages. The equivalent width also decreases in plage. This corresponds to the experience mentioned in the introduction, that the equivalent width of the Mn I 539.47 nm line is about 78.6 mÅ at maximum and it increases to about 79.8 mÅ at minimum. The FWHM does not change from the photosphere to plages, which

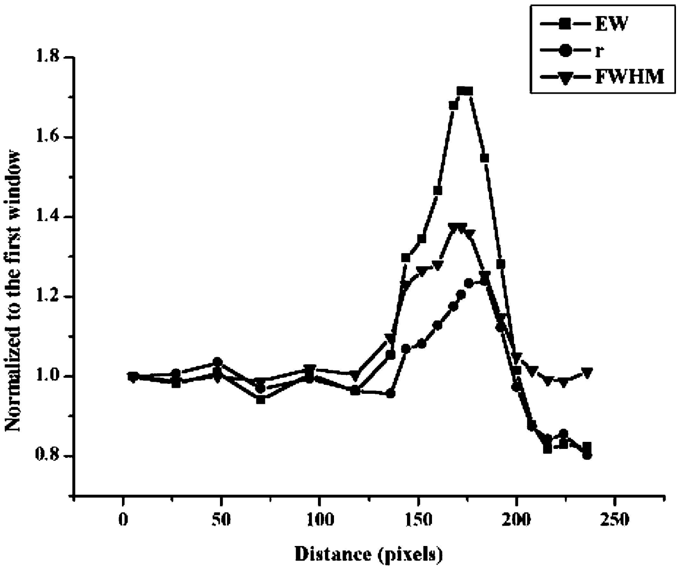

Figure 6. Behavior of the equivalent width, central depth and FWHM width of the line Mn I 539.47 nm in the plage, sunspot, and quiet photosphere of the NOAA AR 9575.

is in accordance with the earlier finding that the FWHM exhibited no significant variation with respect to the plage magnetic field. This was published in a paper of Vince *et al.* (1998) from which we insert a figure here (Figure 7).

To check whether there is any instrumental influence on the intensity variation along the slit, the relative intensity distribution in the continuum was measured in f4VC region (see Figure 5) of the spectrum. There are no significant differences

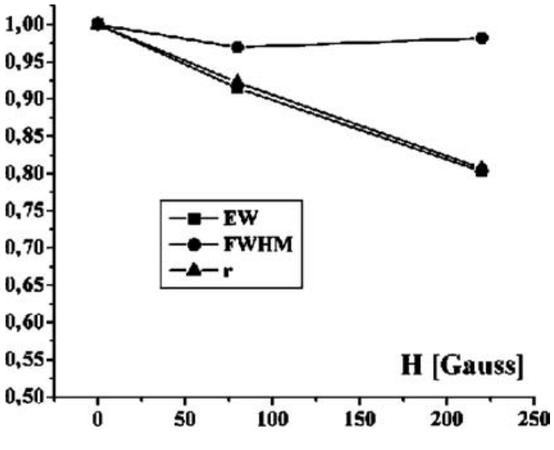

Figure 7. Change of the Mn I 539.47 nm line parameters with the magnetic field strength (the figure is adapted from Vince *et al.*, 1998).

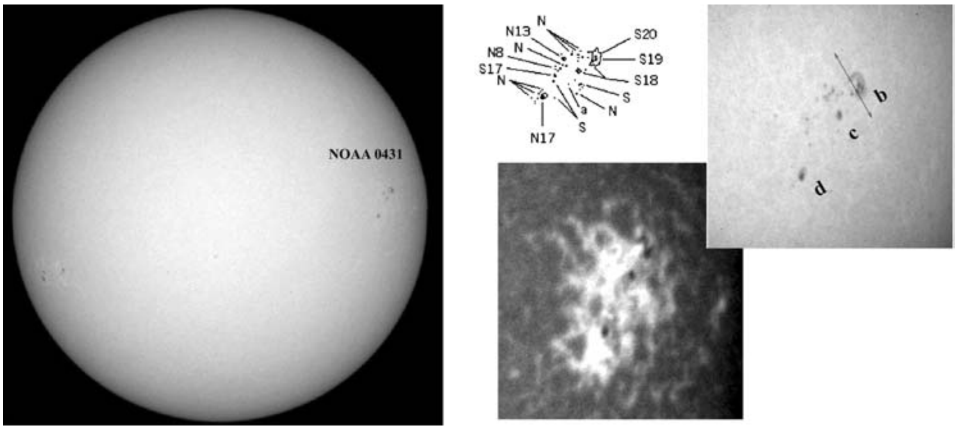

Figure 8. The white-light image of the full solar disc (*left*), the white-light and Ca II K images of the NOAA 0431 active region with the sunspots (*right above* and *middle below*) and the magnetic field intensity values of the sunspots (*middle above*).

between the relative intensities in the strips 1–6 and 17–19 which cover the regions outside the spot.

On 18 August 2003 the spectra of the Mn I 539.47 nm spectral line were observed in three different sunspots of the NOAA 0431 active region and in their vicinity. This active region has been classified as a beta–gamma region, which continued to slowly decay (BBSO Solar Activity Report). Figure 8 shows the white-light image of the whole solar disc (left) and the enlarged part of the Sun in the NOAA 0431 active region (white-light image right above – the three observed spots are labeled by b, c and d; the arrow represents the spectrograph entrance slit's approximate orientation during the observation and its position at spot b). Middle, below, is the Ca II K image of this active region. These images were taken from Big Bear Solar Observatory observational data archive (see *http://www.bbso.njit.edu*). The graph in the middle above indicates the sign of magnetic field (N or S) and its intensity (units are 100 Gauss). The graph was taken from the Crimean Astrophysical Observatory observational data archive (see *http://www.crao.crimea.ua*). As can be seen from the white-light images of Figure 8, the NOAA 0431 active region is rather complex. Beside the three larger sunspots a number of small spots and pores are visible. As a result, the spectra are biased, i.e., beside spectra originating from larger spots (labeled as b, c and d) other smaller spots/pores spectra are evident. The plage region, as can be seen from the Ca II K image, covers an area which is much larger than the projected length of spectrograph entrance slit on the solar disc. Therefore it is not clear which part of the spectra are appropriate to the photosphere. For this reason, the spectrum part of relatively maximal intensity has been chosen to determine the EW, *r* and FWHM parameters for normalization.

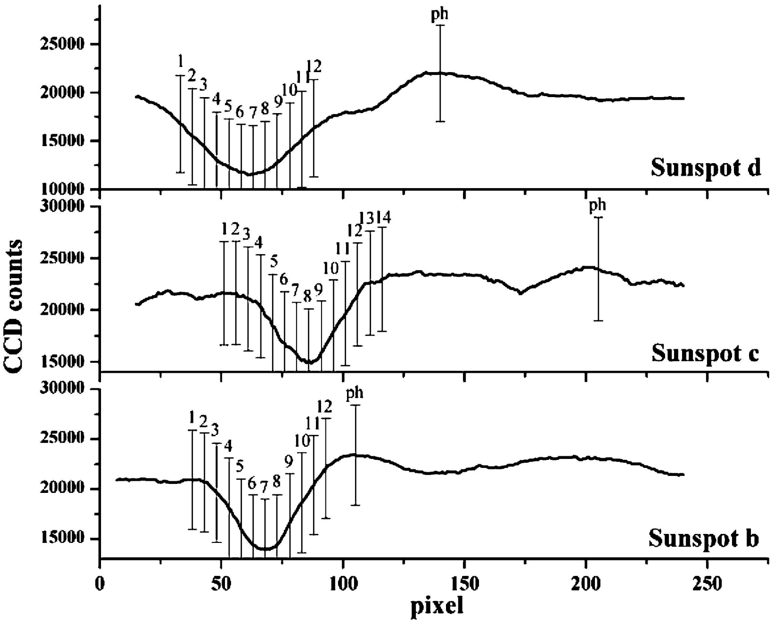

Figure 9. The relative intensity variation along the spectrograph slit and the strips that divide the spectra in that direction.

Perpendicularly to the dispersion axis, the combined spectra were divided into five-pixel-wide strips that cover the nearby photosphere or plage region. Figure 9 shows the averaged relative intensity variation along the spectrograph slit. The vertical straight lines represent the positions of strips, while the horizontal bars at their ends the width of strip. Strips are labeled by numbers except that labeled by "ph" which is chosen for normalization.

The spectra in these strips were averaged to extract a one-dimensional spectrum. After normalization and calibration, the parameters of the Mn I 539.47 nm spectral line profiles were measured.

In Figure 10 the changes of the Mn I 539.47 nm spectral line profile parameters versus strip positions are presented. The values are normalized to the 'ph' value. All three spectral line profile parameters show similar behavior, i.e., they increase toward the spot's penumbra and umbra. The equivalent width shows the most pronounced change up to 60%, the change of depth is about 30%, while the full width at half maximum doesn't vary more than 20%.

3. Line Behavior in the Quiet Photosphere

An indirect probe can also be done to establish the photospheric nature of the Mn I 539.47 nm line: to observe the asymmetry of the line and its center-to-limb variation. This is a signature of a specific correlation of the non-homogeneities in the

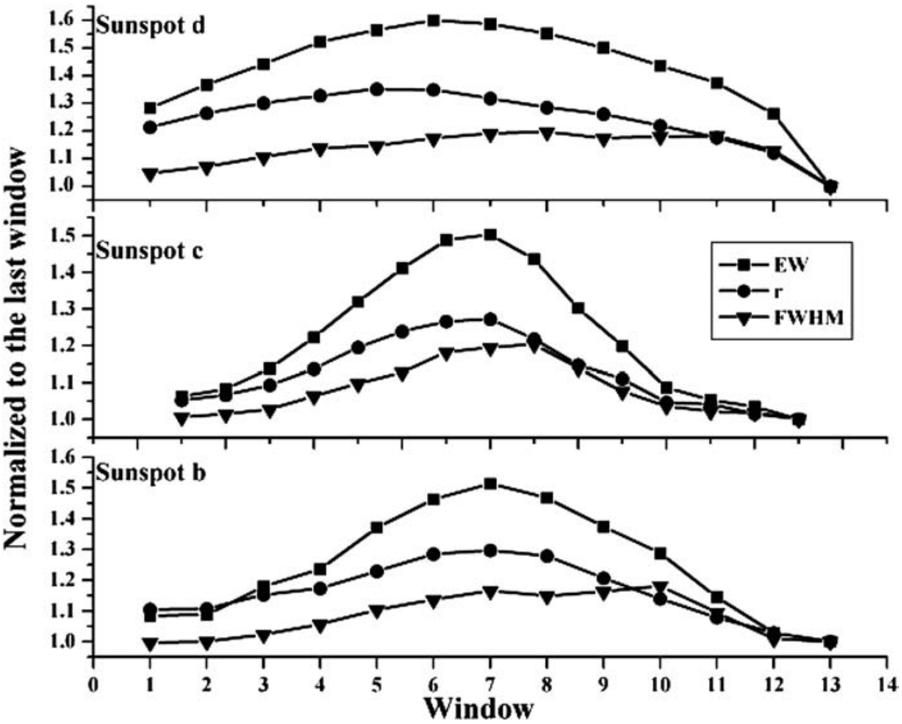

Figure 10. The Mn I 539.47 nm spectral line parameter variations perpendicularly to the dispersion axis.

photospheric intensity and velocity distributions (Dravins, 1982; Gurtovenko *et al.*, 1975). These line profiles have been observed using the spectrograph of the Terskol Observatory in 2002. The observations were carried out on the solar telescope with a main mirror of 65 cm and a focal length of 1775 cm. The collimator and camera mirrors of the spectrograph are 30 cm in diameter and 800 cm in focal length. The grating has 600 lines/mm with a ruled area of 25 cm × 20 cm. The observations were made in the fifth spectral order with a slit width of 25 μm. The spectra were taken by a CCD camera with a 765 × 510 array and 9 μm × 9 μm pixels. For the $\cos\theta$, describing the distances from the center of the solar disc (θ is the heliocentric angle), the following values were adopted: 1, 0.82, 0.6, 0.4, and 0.2.

For each position 10 images were taken with a 55-s time gap between them. Each image was reduced for dark current, scattered light, and averaged along the slit direction. In such a way we obtained 10 spectral records for each heliocentric angle. These records were combined into one 765 × 10 array for every value of heliocentric angle. Finally these 10 spectra were averaged into a one-dimensional record. Using this procedure we avoid the influence of 5-min oscillations and increase the signal-to-noise ratio. The data reduction is aimed at determining the variation of the line profile bisector dependence with $\cos\theta$. The results are depicted in Figure 11.

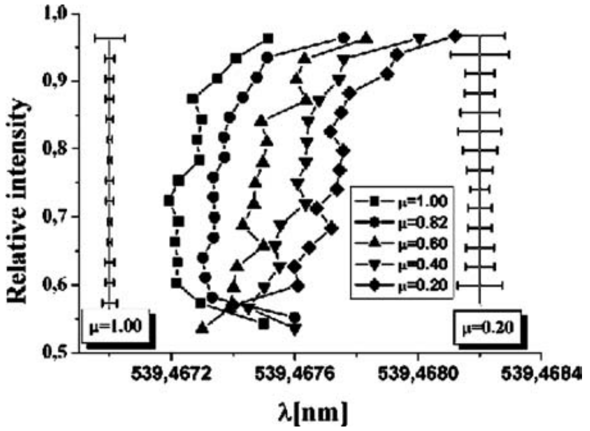

Figure 11. Line bisectors at different distances from the solar disc center. To aid clearness of the graph, bisectors at different heliocentric angles are artificially separated (shifted toward the longer wavelength) from each other by 1 pm. Along the two vertical lines error bars are given for bisector at solar disk center (*left*) and at $\cos\theta = 0.2$ (*right*).

The bisectors exhibit the well-known C-shaped asymmetry and the center-to-limb variation which is typical for the photospheric spectral lines. It seems to be well established that the Mn I 539.47 nm line is definitely of photospheric origin.

The bisector errors were derived from photometric noise (detector and photon noise). It depends on the position in line profile (it is inversely proportional to the slope of the line profile) and proportional to the photometric error for the intensity. The signal-to-noise ratio of our measurements at the continuum intensity was about 1000 at the disk center and decrease toward the limb. It was about 300 near the limb (at $\cos\theta = 0.2$). In Figure 11 the estimated error bars of the bisectors for these two positions are given. The error bars for other positions on the limb are omitted because of clarity of the graph. Their error bars are in between these two extreme cases.

4. Conclusions

By analyzing the center-to-limb variation of the bisectors of observed Mn I 539.47 nm spectral line profiles it is proved that this line is definitely of photospheric origin.

The observed increase of the EW, FWHM and r of the Mn I 539.47 nm line profile from the quiet photosphere or plage regions to the sunspot umbra of the active regions NOAA 9563, 9575, and 0431 are similar: 60–80% of EW, 20–30% of r and 20–35% of FWHM. In the plage of the active region NOAA 9575, the EW decreases by about 20% and the r by about 15%, while the FWHM remains constant with respect to the quiet photosphere. It should be admitted that this feature was only detected in the AR 9575, while we were unable to distinguish facular and photospheric regions on the slit in the case of the AR 9563 and AR 0431, so this claim needs further checking. The increases of these parameters in sunspots are larger than their decreases in plage regions.

Despite the larger influence of the sunspot umbrae on EW and *r* the influence of plages is dominant on these parameters in the spectrum of the Sun as a star since the relative coverage of the solar surface by plages is much larger than that occupied by sunspots. In addition, the intensity of radiation in spots is lower than that in plages. This is the reason why long-term observations of EW and *r* in the solar irradiance spectrum show anti-correlation with Wolf's sunspot numbers. As it has been mentioned, the Mn I 539.47 nm line is under the indirect influence of photons of the Mg II k spectral line (Doyle *et al.*, 2001). Therefore, if this influence is large enough, the parameters of the manganese line could be used as a proxy for the Mg II index, which is an indicator of solar UV flux variation. For the control of the possibly significant influence of sunspots the FWHM could be used since this parameter is sensitive to sunspots, but insensitive to plages. These features of the Mn I 539.47 nm spectral line could be used as indicators of solar irradiance variability caused by plages and sunspots simultaneously. To confirm these conjectures, further spectral observations of different types of sunspots and plages at different heliocentric angles are needed.

Our ultimate goal is to establish an observational program for monitoring of the Mn I 539.47 nm spectral line of the Sun as a star and to simulate the observed activity cycle variation of this line in solar irradiance spectrum taking into account the contribution of different solar features to the Mn I 539.47 nm line profile. For this purpose we plan to construct an automatic, very small, and low cost solar telescope with a powerful spectrograph (spectral resolution about 5,000,000) using a Fabry–Perot or echelle emulating device, for monitoring the solar spectral irradiance variation in the Mn I 539.47 nm line.

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