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SENSITIVITY OF THE MnI 539.47 nm SPECTRAL LINE TO SOLAR ACTIVITY

S. Danilović and I. Vince

Astronomical Observatory, Volgina 7, 11160 Belgrade 74, Serbia and Montenegro

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SUMMARY: CCD observations of the MnI 539.47 nm spectral line in the solar flux made at the Astronomical Observatory in Belgrade between 1994 and 2003 have been reduced and certain line parameters, viz. the equivalent width, full width at half maximum and central depth have been derived. The variation of these parameters with the solar activity has been evaluated. The relative variation of the equivalent width from minimum to maximum of solar activity was found to be 1.4%, while the variation of the central depth is 2.3%. The full width at half maximum remains practically constant.

Key words. Sun: activity - Techniques: spectroscopic - Line: profiles

1. INTRODUCTION

The chromospheric behaviour of the photospheric spectral line of MnI 539.47 nm in the solar spectrum (hereinafter: Mn 539 line) has been a puzzle for a long time. Various mechanisms have been proposed to explain this phenomenon, but the full qualitative explanation was not given until 2001 (Doyle et al. 2001). The variability of the parameters of the Mn 539 line was recognized for the first time on the basis of full-disk observations at Kitt Peak during the period 1979-1985 (Livingston and Wallace 1987). It was concluded that its equivalent width displays an increase of 2% in the solar activity minimum and correlates well with the Ca K 393.3 nm line intensity. These results were confirmed in a report based on extended data (Livingston 1992). Using the same data set, a detailed analysis was performed a few years later (Vince and Erkapic 1998) and a conclusion was arrived at that the equivalent width (EW) and central depth (CD) vary by 1.12% and 1.05%, respectively, during the cycle of solar activity. This line was also included in the so-called "Belgrade Program for Monitoring of Activity-sensitive Spectral Lines of the Sun as a Star", which started in August 1987 (Vince at al. 1988). First results were published in 1992 (Skuljan et al. 1992) and then again in 1993 (Skuljan et al. 1993). The variability of the equivalent width of the Mn 539 line was once again noted, but the measurement errors were large and the values mentioned there have not been confirmed.

This report contains an analysis of the Mn 539 line data acquired during the period 1994-2002, in which a CCD camera was introduced for the detection of solar spectra with the solar spectrograph of the Astronomical Observatory in Belgrade.

2. OBSERVATION AND DATA REDUCTION

The period between 1994 and 2003 covers the increasing phase to the post maximum phase of solar activity. During this period, the observations were typically made in blocks of ten to thirty days per observational season. In 1994 the previously used photometric scanner (Arsenijevic et al. 1988) of the equatorial solar spectrograph (Kubicela 1975) was replaced by a SBIG ST6 CCD camera. The size of the chip of this camera is 8.63 × 6.53 mm (375 × 244 pixels), with 23 × 27 microns of pixel size. The dispersion was about 0.8 pm/pixel, which means that the observed spectral range covered by the CCD camera was about 0.3 nm. Since 1994 the spectrograph system has not been changed and all observations have been made in the same regime. This resulted in a homogeneous set of solar spectra. That is the reason why we have chosen this period for our investigation of the Mn 539 line parameters variation.

In order to obtain a signal-to-noise ratio as high as possible, we have combined our daily images whenever there were more than two CCD images taken on a same day. Due to the specific construction of our solar spectrograph (Kubicela 1975) and specific observational method (spectrograph acts as *camera obscura*), classical flat field corrections to the CCD images cannot be applied since it is not possible to reproduce the same light path during the flat field and spectrum (object) image acquisition. Therefore, we had to introduce a different flat field correction procedure. As the first step, the combined images have been cleaned from imperfections caused, for instance, by dust on the entrance window in front of the CCD camera. For the cleaning procedure, a computer program was written to detect those defects by examining every cross section perpendicular to the dispersion. Imperfections were defined as deviations from the interpolated values around the examined pixel. The interpolation was performed for pixels with intensity higher than 3% or lower than 1% of the maximum intensity in the cross section (background subtracted). These values were obtained empirically by examining several dozens of CCD images. To reduce the random errors, each cross section was smoothed using the Wittaker-Robinson-Vondrak (WRV) method (Vondrak 1969) with a smoothing parameter e = 0.1. A typical spectrum covers at least about 50 to 60 pixel rows perpendicular to the dispersion. Effects of this procedure on spectrum are illustrated in Fig. 1. An example of raw (left) and corrected image (right) is shown in the upper part of the figure. The vertical white line in the CCD image represents a column from which a cross section was extracted. The extracted cross section is shown in the lower left part of the figure. An enlarged detail of the same cross section is shown in lower right part of the figure. As one can see, imperfection caused by dust was eliminated after the first step of procedure, and then applying the WRV method the smaller variations were smoothed.

One-dimensional spectra were extracted from the corrected images by averaging the pixel values across the dispersion from the chosen part of the spectrum. In the example presented in the lower left part of the Fig. 1, the chosen part is located within the two vertical dashed lines.

The continuum normalization and wavelength calibration were then performed. From these spectra the line profile parameters, viz. the equivalent width, full width at half maximum and line depth of the Mn 539 line were finally determined. Spectra were not reduced for instrumental profile since we were interested in determining the relative change of the line profile parameters.

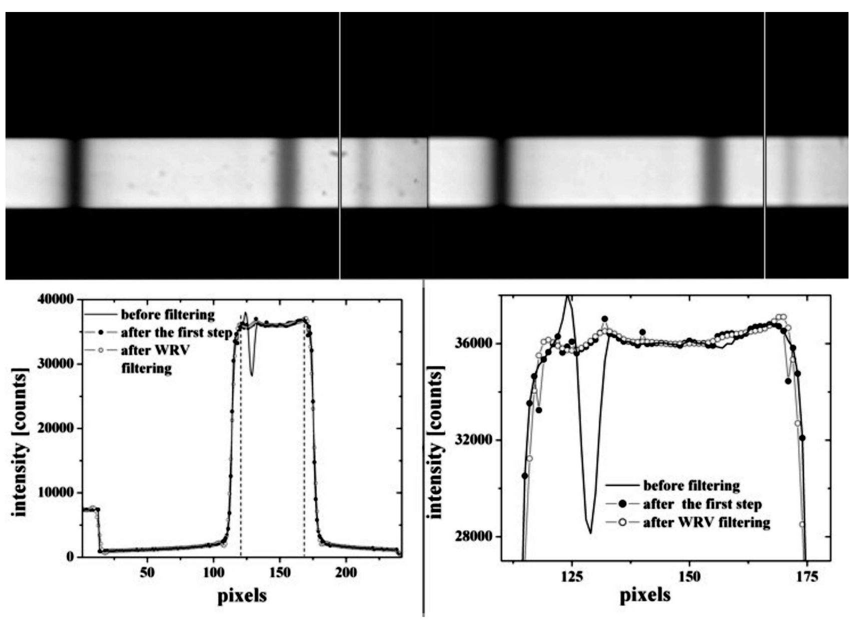

Fig. 1. *Raw CCD image of the solar spectrum (upper left), the same CCD image after correction (upper right), cross section labeled in the upper pictures (lower left), enlarged part of the cross section (lower right).*

3. ANALYSIS AND RESULTS

A preliminary analysis of the variations of the line profile parameters showed a relatively large dispersion. Because of this, we introduced one additional averaging. Namely, we divided our data into two groups, one around the high and the other around the low daily solar activity level. As a measure of daily solar activity level we decided to use the NOAA daily Mg II (c/w) index. This index is used because it is well correlated with the degree of coverage of the solar surface with plages and can be used as a measure of contribution of plages to the solar irradiance variation. On the other hand, the Mn 539 line parameters change significantly in plages (Vince et al. 2000) and are therefore sensitive to the degree of coverage of the solar surface with plages in the solar flux spectrum too. Also, the Mn 539 line is sensitive to the optical pumping of the electrons from lower energy level of transition by photons of the Mg II K emission line peak (Doyle et al. 2001), which is amplified in plage region.

Taking into account these arguments we subtracted from our data the line profile parameters that correspond to the Mg II c/w index in the interval 0.2644 ± 0.0019 for low and in 0.2818 ± 0.0019 for high daily solar activity level. The results of this selection are given in Tables 1 and 2. Table 1 contains the data corresponding to the high level of solar daily activity. The first three columns contain the date (year, month and day) of observation. The fourth column gives the number of observed spectra, as a product of two numbers, where the first number indicates the number of observed series, while the second one is the number of spectra in each series. The daily values of the Mg II (c/w) index are given in the fifth column. The remaining three columns contain the measured equivalent widths (EW), full widths at half maximum (FWHM) and central depths (CD), respectively, of the Mn 539 line. Table 2 contains similar information around the low level of solar activity. In this case there is only one image taken per day, so that the corresponding column has been omitted.

Table 1. Date, number of images, Mg index and parameters of the Mn 539 line for the high level of solar daily activity

YEAR	MONTH	DAY	NI	Mg index	EW [Å]	FWHM [Å]	CD
1999	6	30	1x15	0.2806	0.0727	0.164	0.427
2000	5	17	2x15	0.2821	0.0731	0.165	0.43
					0.0737	0.165	0.43
2000	5	18	2x15	0.2821	0.0734	0.164	0.434
					0.0736	0.165	0.431
2000	5	21	3x5	0.2826	0.0733	0.164	0.432
					0.0734	0.163	0.434
2000	5	22	2x15	0.2816	0.073	0.164	0.429
					0.0736	0.164	0.432
2000	5	23	2x15	0.2804	0.0727	0.164	0.429
					0.0728	0.163	0.429
2000	6	19	2x10	0.2805	0.0734	0.165	0.432
					0.0735	0.165	0.429
2000	6	20	1x10	0.2803	0.0731	0.164	0.43
2000	6	21	1x15	0.2802	0.0735	0.165	0.43
2000	7	10	1x10	0.2818	0.0741	0.165	0.434
2000	7	11	1x15	0.2837	0.0743	0.163	0.438
2000	7	18	2x15	0.2856	0.0729	0.164	0.428
					0.073	0.165	0.43
2000	9	28	1x10	0.2811	0.0722	0.164	0.426
2000	10	4	1x10	0.2804	0.0705	0.163	0.419
2001	9	13	3x10	0.2817	0.067	0.177	0.363
					0.0666	0.177	0.359
					0.0658	0.177	0.358
2001	9	14	2x10	0.2816	0.0681	0.175	0.372
					0.0681	0.175	0.372
2001	10	12	1x10	0.2815	0.0686	0.167	0.397
2001	10	13	1x10	0.2818	0.0699	0.167	0.406
2001	10	15	2x10	0.2815	0.0706	0.167	0.405

Table 1. (continued)

YEAR	MONTH	DAY	NI	Mg index	EW [Å]	FWHM [Å]	CD
					0.0702	0.168	0.402
					0.0704	0.167	0.404
2001	10	16	1x10	0.2818	0.0687	0.167	0.395
2001	10	17	1x10	0.2823	0.068	0.168	0.39
2001	10	18	2x10	0.283	0.0706	0.168	0.398
					0.0707	0.169	0.399
2001	11	8	1x10	0.2832	0.0698	0.17	0.393
2001	11	22	1	0.2821	0.0689	0.176	0.375
2002	3	5	1x10	0.2822	0.0728	0.163	0.428
2002	3	13	2x10	0.2807	0.0733	0.163	0.433
					0.0729	0.163	0.434
2002	3	14	2x10	0.2812	0.0729	0.163	0.434
					0.0723	0.164	0.427
2002	3	18	1x10	0.2827	0.0693	0.161	0.419
2002	4	1	1x10	0.2811	0.0729	0.161	0.435
2002	4	2	2x10	0.2806	0.0732	0.164	0.432
					0.0728	0.162	0.431
2002	4	3	2x10	0.2807	0.0736	0.163	0.436
					0.0729	0.163	0.432
2002	4	16	1x10	0.2831	0.0728	0.161	0.437
2002	4	26	1x10	0.2803	0.0728	0.162	0.438
2002	5	4	1x10	0.2812	0.0735	0.161	0.442
2002	5	7	2x10	0.2836	0.0741	0.163	0.441
					0.0744	0.162	0.445
					0.0731	0.162	0.44
					0.0737	0.161	0.445
2002	5	13	1x10	0.2813	0.0738	0.162	0.441
2002	5	14	1x10	0.2801	0.0736	0.163	0.432
2002	5	22	2x10	0.2806	0.0736	0.162	0.44
					0.0737	0.161	0.442
2002	6	4	1x10	0.2814	0.0727	0.164	0.428
2002	6	20	1x10	0.2799	0.0748	0.162	0.444
2002	8	23	2x10	0.2832	0.0738	0.163	0.439
2003	10	29	1x10	0.2811	0.0736	0.166	0.424

Table 2. Date, Mg index and parameters of the Mn 539 line for the low level of solar daily activity

YEAR	MONTH	DAY	Mg index	EW [Å]	FWHM [Å]	CD
1994	8	22	0.2646	0.0717	0.164	0.422
1994	9	12	0.265	0.0738	0.165	0.425
1994	9	13	0.2646	0.0713	0.163	0.423
1994	9	16	0.2638	0.0712	0.164	0.424
1994	9	28	0.2652	0.0710	0.164	0.421
1995	9	19	0.2644	0.0714	0.166	0.415
1995	10	3	0.2635	0.0726	0.165	0.426
1995	10	7	0.2637	0.0735	0.163	0.435
1995	10	11	0.2655	0.0732	0.163	0.433
1995	10	13	0.2653	0.0704	0.165	0.417
1995	10	14	0.2661	0.0716	0.162	0.430
1995	10	18	0.2657	0.0712	0.164	0.423

Table 2. (continued)

YEAR	MONTH	DAY	Mg index	EW [Å]	FWHM [Å]	CD
1995	10	23	0.2663	0.0732	0.166	0.428
1995	10	30	0.2645	0.0723	0.163	0.428
1996	6	6	0.2646	0.0737	0.162	0.440
1996	6	9	0.265	0.0738	0.163	0.437
1996	7	8	0.2655	0.0707	0.165	0.416
1996	7	13	0.2642	0.0779	0.168	0.435
1996	8	25	0.2656	0.0704	0.162	0.421
1996	9	11	0.2637	0.0719	0.162	0.429
1996	9	30	0.2648	0.0708	0.164	0.415
1996	10	2	0.2641	0.0722	0.165	0.422
1997	5	12	0.2646	0.0752	0.165	0.441
1997	5	13	0.2647	0.0749	0.165	0.438
1997	5	14	0.2645	0.0739	0.164	0.439
1997	5	15	0.2647	0.0737	0.163	0.441
1997	5	17	0.2647	0.0743	0.167	0.423
1997	5	23	0.2656	0.0721	0.162	0.430
1997	6	24	0.2647	0.0758	0.162	0.451
1997	7	2	0.265	0.0761	0.163	0.453
1997	7	13	0.264	0.0751	0.164	0.444
1997	8	21	0.2655	0.0751	0.162	0.449
1997	8	22	0.2652	0.0767	0.162	0.456

In accordance with our initial assumption, the Mn 539 line parameters in the two data sets should be distributed around two values corresponding to the high and low level of the daily solar activity. In order to find out if these samples could be drawn from the same population, we performed Student-t test. Since all three obtained values are larger than table value which corresponds to probability of 0.01 we can say that there is a significant difference between the averages of the two samples.

The average values of the three line profile parameters (EW, FWHM and CD) are obtained from Table 1 for high level and from Table 2 for low level of daily solar activity. The average values of the equivalent width at the high and at the low level of daily solar activity are 0.0721±0.0022 Å and 0.0731±0.003 Å, respectively. The central depth at the high level activity is 0.421±0.023 and at low level is 0.431±0.024. The corresponding values for the full width at half maximum are 0.165±0.004 Å and 0.164±0.002 Å, respectively. The equivalent width from low to high level of solar activity decreases by 1.4%, the central depth decreases by 2.3% while the full width at half maximum increases by only 0.6%.

3. CONCLUSION

At the Astronomical Observatory in Belgrade spectroscopic observations of the MnI 539.47 nm line have been carried out since 1994 using a CCD camera as a detector. During this period the spectrograph system has not been changed. Therefore, a homogeneous observational data set has been collected. Statistical analysis applied to the reduced line parameters (EW, FWHM and CD) shows that EW and CD decrease with increasing solar activity level, while the FWHM practically remains constant. These results confirm some earlier findings that the EW and CD of the MnI 539.47 nm spectral line are sensitive to the solar activity (Livingston 1992, Vince and Erkapic 1998), while the FWHM is almost insensitive to the solar activity (Vince et al. 2000).

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ОСЕТЉИВОСТ СПЕКТРАЛНЕ ЛИНИЈЕ НЕУТРАЛНОГ МАНГАНА НА 539.47 нм НА СУНЧЕВУ АКТИВНОСТ

S. Danilović and I. Vince

Astronomical Observatory, Volgina 7, 11160 Belgrade 74, Serbia and Montenegro

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Оригинални научни рад

CCD посматрања спектралне линије неутралног мангана на 539.47 nm у сунчевом флуксу извршена од 1994. до 2003. године редукована су и одређени су њени параметри: еквивалентна ширина, полуширина и централна дубина. Нађена је промена ових параметара у зависности од сунчеве активности. Релативна промена еквивалентне ширине од ниске до високе сунчеве активности износи 1.4%, а централне дубине 2.3%. Полуширина линије практично се не мења са променом нивоа активности Сунца.