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Preliminary report

INVESTIGATIONS OF THE MnI 539.47 nm AND MnI 542.04 nm LINES IN SOLAR PLAGES

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SUMMARY: We observed the MnI 539.47 nm and 542.04-nm line profiles in the quiet photosphere and plage regions in 1998 and 2001, and measured the full widths at half maximum, equivalent widths and depths of these profiles. The relative changes of the MnI 539.47 nm line parameters, normalized to the values obtained for quiet photosphere, as a function of magnetic field strength in plages is analyzed. We found, for plage region observed in 1998, that both the equivalent width and the depth of the line profile decrease with increasing strength of magnetic filed in plage at a rate of 9x10^{-4}/Gauss, but the full width at half maximum does not show any significant regular changes. Based on these results, the variations of the MnI 539.47 nm spectral line in solar flux with activity cycle could be explained by the variation of solar surface coverage with plages. For observations in 2001, the equivalent width and the depth of this line profile also decrease with increasing strength of magnetic filed in plage, but there are significant differences in the behavior of line parameters in comparison with the 1998 values.

Comparison of changes of the MnI 539.47 nm line parameters with the parameters of the MnI 542.04 nm line in 1998 shows a clear discrepancy between them. On the contrary, in 2001 the full widths at half maximum and the equivalent widths of these two lines behaved in a similar fashion.

Key words. Sun: faculae, plages – Techniques: spectroscopic – Line: profiles

1. INTRODUCTION

In 1986, at the Astronomical Observatory in Belgrade, an observational program for investigation of the solar photospheric spectral line variation during solar cycle activity was introduced. Several spectral lines with significant variation were found (Vince et al. 1992) with the MnI 539.47 nm as the most interesting. The equivalent width of this line, measured for the full solar disk, shows a cycle variation higher than 1% (Livingston 1992, Vince and Erkapic 1997, Danilovic and Vince 2004). This unusually high degree of variation motivated us to investigate this line from various aspects.

To explain of the MnI 539.47 nm line behavior we have proposed several hypotheses. One of them was that the variations of the MnI 539.47 nm line were caused by the influence of plages. To check this hypothesis, we have observed the MnI 539.47 nm spectral line in plages and quiet photosphere. In addition this spectral line it seems likely sensitive to chromospheric ultrviolete radiation. Namely,recently, using multi-line and multi-species NLTE calculation, Doyle et al. (2001) showed that the MnI 539.47 nm line is sensitive to optical pumping of electrons of the common lower energy level of the MnI uv1 spectral line (297.5 nm) and the MnI 539.47 nm line by the MgII k chromospheric line photons. According to these results, there may be a difference in spectral line profile parameters in plages (where the photon emission in the MgII k line is enhanced) with different brightness and magnetic field strengths between the MnI 539.47 nm line and any other manganese spectral lines, which are formed in the transition from different lower energy levels than the MnI 539.47 nm line. To check this assumption, for a comparison line we have chosen the MnI 542.04 nm spectral line.

2. CHARACTERISTICS OF MANGANESE SPECTRAL LINES

The lower energy level of the MnI 539.47 nm line is 0 cm^{-1} and the upper one is 18531.64 cm^{-1}. The electronic configuration of the transition is $\mathbf{3d^5\ 4s^2\ \text{-}3d^5\ (^6S)4s4p(^3P^o)}$. The transition takes place from term $\mathbf{a\ ^6S}$ to term $\mathbf{z\ ^8P^o}$.

For comparison of the Mn 539.47 nm line behavior in plages and quiet photosphere with any other line, it is necessary that the comparison line forms in the similar conditions in the solar atmosphere. Thus, one of the most important criteria in choosing the proper spectral line was the height of its formation in the photosphere. In the first step, according to this criterion, we have selected 14 spectral lines. From these lines we have finally chosen the MnI 542.04 nm line. The lower energy level of this line is 17282 cm^{-1} and the upper one is 35725.85 cm^{-1}. The electronic configuration of the transition is $\mathbf{3d^6\ (^5D)4s\text{-}3d^5\ (^6S)4s4p(^1P^o)}$. The electronic transition takes place from term $\mathbf{a\ ^6D}$ to term $\mathbf{y\ ^6P^o}$. Therefore, the MnI 539.47 nm line has no common energy levels with the MnI 542.04 nm line. The wavelength of the MnI 542. nm line is close to that of the MnI 539.47 nm line. This ensures very similar deformation of the measured profiles of the two lines caused by spectrograph elements. Besides, the profile of the 542.04 nm spectral line is broadened by its hyperfine components similarly to the Mn539.47 nm line profile. The Lande-factors of these lines have comparable values (the effective Lande-factors of the 539.47 nm and 542.04 nm lines are 1.86 and 1.21 respectively). In addition, the line profiles broadened due to the splitting of hyperfine structure components are less sensitive to magnetic field than for lines without hyperfine structure components. Basic parameters of the two lines are given in Table 1.

Table 1. Basic parameters of the considered spectral lines

λ (nm)	E_p (eV)	Log (EW/λ)	H_W (km)	log (gf)
542.04	2.13	-4.845	191	-1.48
539.47	0.0	-4.860	248	-3.57

Data in table are given in the following order: wavelengths of the spectral lines, energies of the lower levels of transition, relative equivalent width (in Fraunhofers), height H_W of formation derived from the observed equivalent widths and logarithm of *gf* values (g is the statistical weight and f is the oscillator strength of transition) derived also from the observed equivalent width (the last two parameters were taken from Gurtovenko and Kostik (1989)).

3. OBSERVATIONS AND REDUCTIONS

The observations of the MnI 539.47 nm and the MnI 542.04 nm spectral lines were carried out at the Crimean Astrophysical Observatory with the 90 cm solar telescope which supplied the double magnetograph. The equivalent focal length of the telescope was about 50 m, giving a solar image of 46.5 cm in diameter at the spectrograph entrance slit. The double magnetograph was constructed on the basis of two separate spectrographs. Their gratings had 600 grooves per mm. The grooved area of the gratings was 200 x 300 mm. Dispersion in the fifth order was 100 mm/nm. The electro-optical modulator (KDP crystal and polaroid) and the Roshon prism were putt behind the spectrograph slit. After the Roshon prism there formed two light beams each of them were used in each of the two spectrographs separately. Collimator and camera mirrors of both spectrographs were 10 m and 20 m in focal length respectively. The slits of the photometer were placed at the camera focal plane of each spectrograph. During the observations, one of the magnetographs was used to find the observed positions on the solar disk and to measure the magnetic field. The other magnetograph was used as a photometer, to record the profiles of the spectral lines. The spectral line profiles were scanned by rotation of the grating. In the meantime, the guiding system kept the image of the sun at the spectrograph slit. The manganese line profiles were recorded in the fourth order of the spectrum. Magnetic fields were measured in the FeI 525.35 nm line in fifth order of the spectrum. This line has a simple splitting, while the MnI 539.47 nm has complicated splitting. The FeI 525.35 nm line has Lande factor of g=1.5. We observed three series with six line profiles in each of them.

3.1. Observations in 1998

The first series of the MnI 539.47 nm and 542.04 nm lines were recorded at the vicinity of the solar disk center on 20th August 1998. At that position, the line-of-sight component of magnetic field was equal to zero (these data we denote by H0). The second series was observed on 24th August 1998 at L=0 and B=-29. At that position, the line-of-sight component of magnetic field was 80 Gauss (these data we denote by H1). Finally, the third series was taken at the same region on the same day, but with line-of-sight magnetic component of 220 Gauss (we denote these data by H2). The spectrograph entrance slit covered an area of 1"x1" on the solar disk. The recordings of the spectral line profiles were made with two polarizations. The profiles were recorded with the photometer slit width of 3.0 pm and digitized by a digitizer with step of 0.320 pm. Linear dispersion on recording tape was 0.0032 nm/mm. The accuracy of reproduction of spectral line profiles in wavelength was ± 0.50 pm. The error of continuum level determination was 3%. Six profiles from each series were measured, averaged and normalized to continuum intensity. These profiles were used for further analysis.

3.2. Observations in 2001

The observation was taken on 7th August 2001 with same method of observation as in the previous case. The first series was made in the vicinity of the solar disk center, where the line-of-sight component of the magnetic field was equal to zero (H0 data). The second series was made in the active region L=+9, B=+17, in the place where the line-of-sight component of the magnetic field amounted to 510 G (H2 data). The third series was taken in the same active region, with the line-of-sight magnetic component of 130 G (H1 data). The profiles were recorded with the photometer slit width of 3.0 pm and digitized by a digitizer with step of 0.229 pm. The spectrograph entrance slit covered an area of 1"x1" on the solar disk. Linear dispersion on recording tape was 0.0023 nm/mm. The accuracy of reproduction of spectral line profiles was ± 0.54 pm. The error of continuum level determination was 3%. In each of the series four line profiles were recorded, averaged and normalized to continuum intensity. These profiles were used for further analysis.

4. ANALYSIS AND RESULTS

We analyzed the changes of the line profile parameters as a function of magnetic field strength for both considered manganese lines. In Fig. 1, as an illustration, the line profiles of the MnI 539.47 nm line obtained in 1998 are presented.

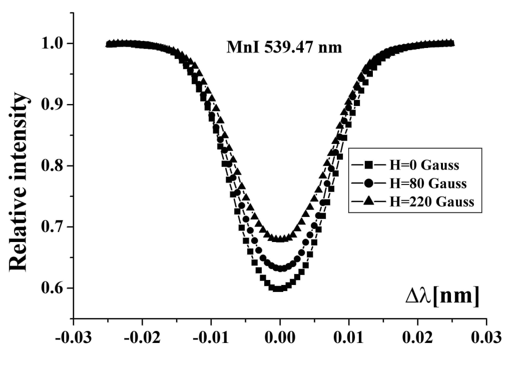

Fig. 1. *The MnI 539.47 nm line profiles for different magnetic field strengths (observations of 1998).*

Table 2. Parameters of the MnI 539.47 nm line measured in 1998 for the three values of magnetic field strength

H (Gauss)	EW (nm)	FWHM (nm)	CI	d
0	0.00703	0.0170	0.596	0.404
80	0.00643	0.0164	0.627	0.373
220	0.00564	0.0165	0.674	0.326

It is evident that the shape of the MnI 539.47 nm line profile varies with the strength of magnetic field in plage. The equivalent width (**EW**), the full width at half maximum **(FWHM)**, residual intensity (**CI**), i.e. the depth at the line profile minimum (**d**) of the line profiles were measured. In Table 2 the results of these measurements are given.

Table 3. Relative changes of parameters of the measured in 1998 for the three values MnI 539.47 nm line of magnetic field strength

H (Gauss)	EW	FWHM	CI	d
0	1.000	1.000	1.000	1.000
80	0.915	0.967	1.053	0.922
220	0.8030	0.975	1.131	0.807

With the excepting of the residual intensities, all these parameters decrease with increasing magnetic field strength. The relative changes of these parameters with respect to their values in quiet photosphere (magnetic filed strength equal zero) are presented in Table 3.

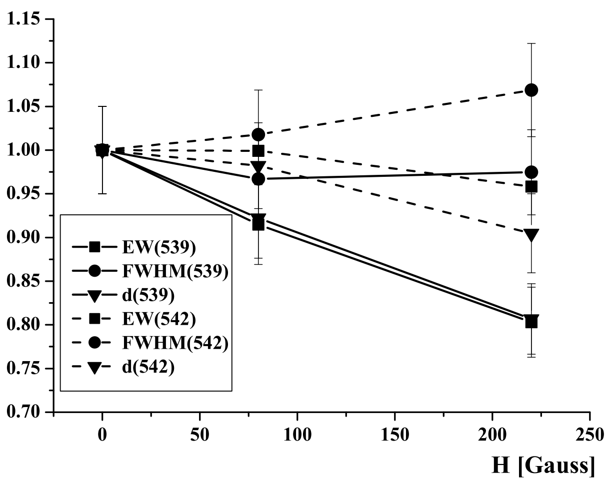

Fig. 2. *The relative changes of the MnI 539.47 nm (solid lines) and MnI 542.04 nm (dashed lines) line parameters normalized to the values of H=0 Gauss and the corresponding estimated error-bars (observations of 1998).*

The relative changes of these parameters normalized to the values of H0 are presented in Fig. 2 (solid lines). We see that the **EW** and **d** of the MnI 539.47 nm line monotonically decrease with increasing magnetic field strength in plages reaching the value of about 20% at 220 Gauss, while the **FWHM** changes only by about 3%. We find that the **EW** and **d** of the MnI 539.47 nm line decrease with increasing strength of magnetic field in plage by a factor of 9×10^{-4}per Gauss. The **EW** and **d** follow the cycle variation of these line parameters in solar flux. Assuming an average magnetic field of 500 Gauss in the plage regions, about 4% of the solar hemisphere needs to be covered with such plages at the activity maximum to account for the about 2% observed variation of **EW** and **d** of the MnI 539.47 nm line in solar flux during a solar cycle. If one takes into account that an average plage area is about 0.5 % of the solar hemisphere, it turns out that about eight plages (active) regions could suffice to explain the decrease of the MnI 539.47 nm line parameters for about 2% at maximum of solar activity. Consequently, our observational results show that the cycle variation of the MnI 539.47 nm spectral line can be explained by the variation of solar surface coverage by plages. The unusual behavior of the **FWHM** remains for further investigations.

Table 4. Parameters of the MnI 542.04 nm line measured in 1998 for the three values of magnetic field strength

H (Gauss)	EW [nm]	FWHM [nm]	CI	d
0	0.00745	0.0212	0.664	0.336
80	0.00744	0.0216	0.670	0.330
220	0.00714	0.0227	0.696	0.304

Table 5. Relative changes of parameters of the MnI 542.04 nm line measured in 1998 for the three values of magnetic field strength

H (Gauss)	EW	FWHM	CI	d
0	1.000	1.000	1.000	1.000
80	0.999	1.018	1.009	0.982
220	0.958	1.069	1.048	0.905

The parameters of MnI 542.04 nm line were measured in the same plages as those of the MnI 539.47 nm line. These data, resulted from observations that were made at the same position and at the same time as for the MnI 539.47 nm line. The obtained parameters are given in Tables 4, 5 and their relative changes with magnetic field strength are shown in Fig. 2 (dashed lines). From Table 5 and Fig. 2 one can see that the **FWHM** values, contrary to those of the MnI 539.47 nm line, increase with magnetic field strength in plages (at least up to 220 Gauss), where they are larger for about 7% with respect to the values for zero magnetic field. On the other hand, **EW** of the MnI 542.04 nm line only slightly decreases at 80 Gauss, and then decreases for about 4% at 220 Gauss. **d** decreases for about 10% at 220 Gauss. These results show a clear discrepancy between the changes of the MnI 539.47 nm and the MnI 542.04 nm line parameters in solar plages. This may be due to optical pumping of the electrons from the lower energy level of the uv1 manganese line (which has a common lower energy level with the MnI 539.47 nm line) by photons of the MgII k line, as it was demonstrated in the paper by Doyle et al. (2001). To confirm these conclusions, we plan to repeat this kind of observations for the MnI 543.25 nm spectral line, which also has the common lower energy level of transition with the MnI 539.47 nm line.

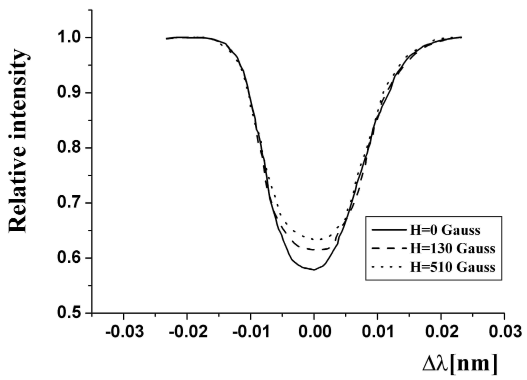

Fig. 3. *The MnI 539.47 nm line profiles for different magnetic field strength (H0 - 0 Gauss. H1 - 130 Gauss, H2 - 510 Gauss. Observations from 2001).*

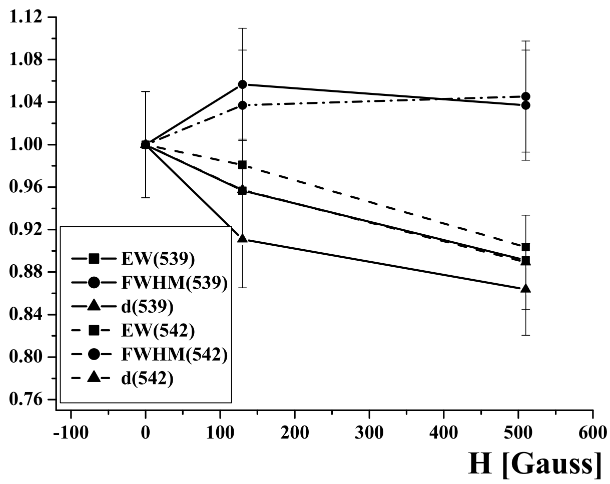

Fig. 4. *The relative changes of the MnI 539.47 nm (solid lines) and MnI 542.04 nm (doted line) line parameters normalized to the values of H=0 Gauss and the corresponding estimated error-bars. (Observations of 2001).*

The method of analysis of the data for 2001 observations is the same as for 1998. Therefore, only the results of this analysis will be shortly presented here. In Fig. 3 the reduced line profiles of the MnI 539.47 nm line are shown.

Parameters, **EW, FWHM, CI** and **d** of the MnI 539.47 nm line profiles were derived and the results are given in Table 6. In Table 7 and in Fig. 4 the relative changes of these parameters as compared to their values in quiet photosphere (zero magnetic filed) are presented (solid lines). The **EW** and **d** of the line profile decrease with increasing magnetic field strength, while its **FWHM** increases from quiet photosphere to plage region, but does not change despite the increasing magnetic field strength, by this increase. The **EW** of the MnI 539.47 nm line decreases, with increasing strength of magnetic field from 0 to 130 Gauss in plage by a factor of 3×10^{-4}per Gauss, and by a factor of 2×10^{-4} per Gauss between 130 and 510 Gauss. The **d** decreases with increasing strength of magnetic field from 0 to 130 Gauss by a factor of 7×10^{-4}per Gauss, and from 130 to 510 Gauss by a factor of 1×10^{-4}per Gauss. Note the abrupt change of the **d** gradient between regions lower and higher than 130 Gauss.

Table 6. Parameters of the MnI 539.47 nm line measured in 2001 for the three values of magnetic field strength

H (Gauss)	EW (nm)	FWHM (nm)	CI	r
0	0.00727	0.0164	0.574	0.426
130	0.00696	0.0174	0.612	0.388
510	0.00648	0.0170	0.632	0.368

It is obvious that **EW** and **d** in 2001 behave differently than in 1998. The gradients of these two parameters remain constant in 1998, and change with increasing magnetic field in 2001. This is another indication that this plage region differs from that observed in 1998. The gradients of relative changes of **EW** and **d** between 130 and 510 Gauss for 2001 are about 5-9 times smaller than those in 1998. This is also indication that the 2001 plage region differs from that in 1998.

Table 7. Relative changes of parameters of the MnI 539.47 nm line measured in 2001 for the three values of magnetic field strength

H (Gauss)	EW	FWHM	CI	d
0	1.000	1.000	1.000	1.000
130	0.957	1.057	1.066	0.911
510	0.891	1.037	1.101	0.864

The measured parameters of the MnI 542.04 nm line for 2001 are presented in Table 8. These data were derived from observations that were made at the same position and at same time as for the MnI 539.47 nm line. The relative changes of these parameters with magnetic field strength are shown in Table 9 and in Fig. 4 (dotted lines). We can conclude that all the parameters of the MnI 542.04 nm line behave (contrary to the behavior in 1998) in a similar way as the parameters of the MnI 539.47 nm line.

From Tables 2, 4, 6 and 8, it is obvious that there are some differences in the line profile parameters observed at the center of the solar disk in 1998 and 2001. Moreover, they are also different from the parameters contained in the well-known Liege solar atlas (Delbouille et al. 1973) or in the atlas of Moore et al. (1966). The differences of **d** (**CI**) and **FWHM** could be due to the influence of the instrumental profile, but the **EW**, in principle, has to be independent of it. For example, the **EW**, of the MnI 539.47 nm line and the MnI 542.04 nm line, listed in Tables of Solar Spectrum Wavelengths (Moore et al. 1966) are 7.4 pm and and 7.8 pm, respectively, while our measurements give systematically lower values (up to 3.5%). Therefore, these differences need some explanation. Profiles of the spectral lines are determined by temperature, turbulent velocity, density, and other parameters of plasma. To avoid the effects of local differences due to the fine structure of solar atmosphere (granulation, plages, pores, small spots etc.), the solar spectral lines for the atlas (e.g. Delbouille et al. 1973) are usually taken with a slightly out of focus image, i.e. with solar image not focused exactly on the slit of the spectrograph. The height of the spectrograph slit is, as a rule, more than 10 arcsec. In our observations, the height of the spectrograph slit was 1 arcsec and the image of the sun was focused on the slit of the spectrograph. That is probanly why our EW values are different from those in the solar atlases. The differences in the spectral line parameters taken at solar disk center derived from our observations in 1998 and in 2001 may be also caused by different local plasma conditions at the places where the profiles were recorded.

Table 8. Parameters of the MnI 542.04 nm line measured in 2001 for the three values of magnetic field strength

H (Gauss)	EW [nm]	FWHM [nm]	CI	d
0	0.00762	0.0208	0.648	0.352
130	0.00747	0.0215	0.663	0.337
510	0.00688	0.0217	0.687	0.313

Table 9. Relative changes of parameters of the MnI 542.04 nm line measured in 2001 for the three values of magnetic field strength

H (Gauss)	EW	FWHM	CI	D
0	1.000	1.000	1.000	1.000
130	0.981	1.037	1.023	0.957
510	0.904	1.045	1.060	0.889

5. CONCLUSION

In this paper we demonstrated that in plage region, observed in 1998, the **EW** and **d** of the MnI 539.47 nm line decrease with increasing strength of magnetic field reaching the value of about 20% at 220 Gauss, while the **FWHM** changes only for about 3%. We find that the **EW** and **d** of the MnI 539.47 nm line decrease with increasing strength of magnetic field in plage by a factor of 9×10^{-4}per Gauss. The **EW** and **d** behave in pace with cycle variation of these line parameters in solar flux. Based on these results, the variation of the MnI 539.47 nm spectral line in solar flux with the activity cycle could be explained by the variation of solar surface coverage with plages. In contrast by this, the **FWHM** of the MnI 542.04 nm line increases with magnetic field strength in plages (at least up to 220 Gauss), where it is about 7% larger than the value with zero magnetic field. The **EW** of the MnI 542.04 nm line only slightly decreases at 80 Gauss, and then decreases for about 4% at 220 Gauss. The **d** decreases to about 10% at 220 Gauss. Contrary, in 2001 the **FWHM** and the **EW** of these two lines behave more similarly to each other. The **EW** and **d** of the line profile decrease with increasing magnetic field strength, while its **FWHM** increases from quiet photosphere to plage region, but remain almost constant within the plage region, despite the increasing magnetic field strength.

To explain these differences in behaviour, we introduced two assumptions. The first is that there are at least two types of plages with different physical parameters (perhaps amenable to different magnetic field strengths), which have significantly different influence on these two manganese spectral lines. For example, observations show that in plages, the plasma temperature grows (statistically) with the increasing magnetic field (except for sunspots). The second assumption is that the observed discrepancy is due to the changes of the MgII k line emission component in different plages which, by means of optical pumping mechanism, influences the MnI 539.47 nm line profile.

Unfortunately, the observations and results of analyses presented here are not sufficient to definitively clarify neither the physical origin of different behaviour of the MnI 539.47 nm line in different plage regions observed in 1998 and 2001, nor the different behaviour of the MnI 539.47 nm and the MnI 542.04 nm lines in the same plage in 1998. Further observations and theoretical investigations are necessary for the explanation of the results obtained.

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ИЗУЧАВАЊЕ ЛИНИЈА MnI 539.47 nm И MnI 542.04 nm У СУНЧЕВИМ ФАКУЛАМА

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Претходно саопштење

Извршена су посматрања спектралних линија MnI 539.47 nm и MnI 542.04 nm у мирној фотосфери и у областима факуларног поља у 1998. и 2001. години и измерене су еквивалентна ширина, полуширина и дубина профила тих линија. У раду су анализиране промене нормираних параметра ових линија у односу на мирну фотосферу у зависности од јачине магнетног поља у факуларним пољима. Нађено је да еквивалентна ширина и дубина линије MnI 539.47 nm у 1998. години опада са порастом интензитета магнетног поља брзином од 9×10^{-4}/Gauss, али полуширина линије не показује значајнију промену. На основу ових резултата, променом величине факуларних поља на сунчевој површини, могла би да се објасни промена параметара профила те линије у флуксу Сунца у току циклуса активности.

Упоређивање промене параметара ове линије са параметрима линије MnI 542.04 nm показује значајну разлику у понашању ових двеју линија у факуларним пољима у посматрањима из 1998. године. Међутим, резултати добијени из посматрања 2001. године се разликују од оних у 1998. години, јер не показују значајну разлику између понашања еквивалентне ширине и полуширине тих спектралних линија у факуларним пољима.