CENTER-TO-LIMB VARIATION OF THE Mn I 539.5 nm AND THE Mn I 543.2 nm LINE PROFILES

I. Vince[1], **O. Andriyenko**[2], **O. Vince**[1]

[1] *Astronomical Observatory in Belgrade*
Volgina 7, 11160 Belgrade, Yugoslavia
e-mail: ivince@aob.bg.ac.yu

[2] *International Centre for Astronomical, Medical and Ecological Research*
27 Akademika Zabolotnoho, 03680 Kyiv, Ukraine
e-mail: olexa@mao.kiev.ua

ВАРИАЦИИ ПРОФИЛЕЙ ЛИНИЙ Mn I 539.5 нм И Mn I 543.3 нм ОТ ЦЕНТРА К КРАЮ ДИСКА СОЛНЦА, Винче И., Андриенко О., Винче О. – Для того чтобы найти влияние различных атмосферных слоев и грануляции на профили линий Mn I 539.5/543.3 нм, мы провели наблюдения этих линий на различных гелиоцентрических углах θ ($\cos\theta$ = 1.0, 0.82, 0.6, 0.4, 0.2). Наблюдения проводились на солнечном телескопе обсерватории Терскол. Были измерены полуширина, эквивалентная ширина и центральная глубина профилей линий. *EW* и *FWHM* обоих линий увеличиваются с гелиоцентрическим углом, в то время как центральная глубина уменьшается для линии Mn 543.3 нм и несколько увеличивается возле лимба для линии Mn 539.5 нм. Для этих линий были вычислены модельные профили в ЛТР-приближении с учетом сверхтонкой структуры, было проведено их сравнение с наблюдениями.

In order to find the influence of different atmospheric layers and the granulation on profiles of Mn I 539.5/543.3 nm lines we observed them at different heliocentric angles, θ ($\cos\theta$ = 1.0, 0.82, 0.6, 0.4, 0.2). Observations were carried out on the solar telescope at the Terskol Observatory. Full width at half maximum (*FWHM*), equivalent width (*EW*) and central intensity of line profiles were measured. *EW* and *FWHM* of both lines increase with heliocentric angle, while the *CI* decrease for the Mn 543.3 nm line and slightly increase near the limb for the Mn 539.5 nm line. Synthetic profiles of these lines were calculated under LTE assumption taking into account the hyperfine structure and compared with observed data.

INTRODUCTION

It is an observational fact that the equivalent width of the Mn I 539.5 nm line, measured for the full solar disk, shows activity cycle variability about 2 % [1]. As the Mn I 543.2 nm line has the same lower energy level of transition as the Mn I 539.5 nm line, it is interesting to examine its variability too. For explanation of this variability we used several hypotheses [2] and tested them by various observations and synthetic line profile calculations.

We investigated theoretically (see, *e.g.*, [3]) and experimentally (see, *e.g.*, [4]) the temperature sensitivity of the Mn I 539.5 nm line and concluded that it is rather high but not enough for explanation of the activity cycle variation of line parameters. We have supposed that this variation is caused by the influence of plages and other atmospheric features. Our synthetic line profile calculations, using models of quite sun, plages and bright network elements, did not support that hypothesis. However, recently it has been established that the cyclic variations of the Mn I 539.5/543.2 nm lines are mostly due to the influence of plage variability during the activity cycle. Namely, these lines are sensitive to optical pumping in a transition which overlaps with the Mg II k line [5] and this pumping is very enhanced in plages. It has been also experimentally shown that there are differences in behavior of line profiles in plages between the Mn I 539.5 nm line and the Mn I 542.04 nm line, the latter line has another lower energy level than the Mn I 539.5/543.2 nm lines [6].

The results mentioned above clearly indicate that for understanding the behavior of the Mn I 539.5/543.2 nm lines it is necessary to study them from different aspects. Our goal is to clarify the influence of different atmospheric layers on the profile of Mn I 539.5/543.2 nm lines, so we observed them at different heliocentric angles, θ, ($\cos\theta$ = 1.0, 0.82, 0.6, 0.4, 0.2). Full width at half maximum (*FWHM*), equivalent width (*EW*) and central intensity (*CI*) of the line profile were measured.

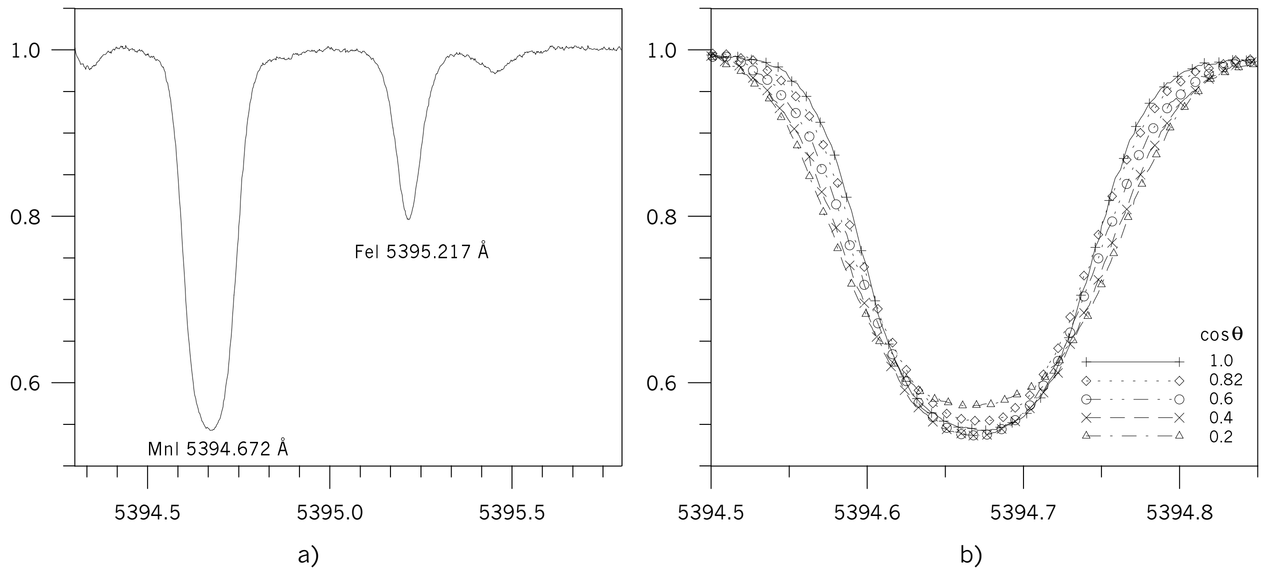

Figure 1. The average over solar disk spectrum near the Mn I 539.5 nm spectral line (a) and the Mn I 539.5 nm spectral line profiles for different heliocentric angles (b)

Synthetic profiles of these lines were calculated under LTE assumption and taking into account the hyperfine structure. We computed the line profiles without hyperfine structure as well. Computed line profile parameters (*EW*, *FWHM*, and *CI*) were compared with observed ones.

OBSERVATIONS AND REDUCTIONS

Observations were carried out on the solar telescope of Terskol Observatory. Focal length and diameter of the telescope main mirror are 1775 cm and 65 cm, respectively. The collimator and the camera mirrors of the spectrograph are 30 cm in diameter and have 800 cm focal lengths. The grating has 600 lines/mm with grooved area of 25×20 cm^2. Observations were made in the fifth spectral order with 25 μm width of the entrance slit. The spectra were taken by a CCD camera with 765×510 array and 9×9 μm^2 pixel size. Procedure of taking images was the same for both lines (Mn I 539.5/543.2 nm). For each position on the solar disk (heliocentric angle $\cos\theta = 1.0, 0.82, 0.6, 0.4, 0.2$) ten images were taken with 55 s time gap between them. Each image was reduced for dark current and scattered light and then averaging along the slit direction was performed. In such a way we obtained 10 spectral records for each heliocentric angle. The records were combined into one 765×10 array for every value of $\cos\theta$. Further treatment was made in Belgrade. The arrays were averaged along short (temporal) dimension with help of the IRAF program package. Thus we obtained spatially and temporally averaged line profiles. Normalization to the local continuum and wavelength calibration were performed with the SPE program package. Measuring of the line parameters (*EW*, *FWHM*, and *CI*) was also performed with SPE.

Averaged profiles of the Mn I 539.5/543.2 nm lines are shown in Fig. 1 and Fig. 2 (after averaging in IRAF and normalization and calibration in SPE). From the enlarged parts of the spectra it is obvious that shape of the line profiles vary with $\cos\theta$.

Calculations of synthetic spectra were performed using SPECTRUM (PC-based Stellar Spectral Synthesis Program) program package made by R. O. Gray. The hyperfine structure of the manganese lines was taken into account. In order to make a good fit with the observed spectra (which were taken from High Resolution Solar Spectrum Atlas) the relative intensity, *i.e.*, gf-factors of six hyperfine structure components were taken from [7] and [8]. For microturbulence velocity we took 1.5 km/s value.

RESULTS AND CONCLUSION

The center-to-limb variations of observed and calculated (with and without hyperfine components) parameters (*EW*, *FWHM*, and *CI*) for the Mn I 539.5 nm and Mn I 543.2 nm lines are shown in Fig. 3 and Fig. 4. One can see that the observed *EW* and its variation with $\cos\theta$ agree well with calculated

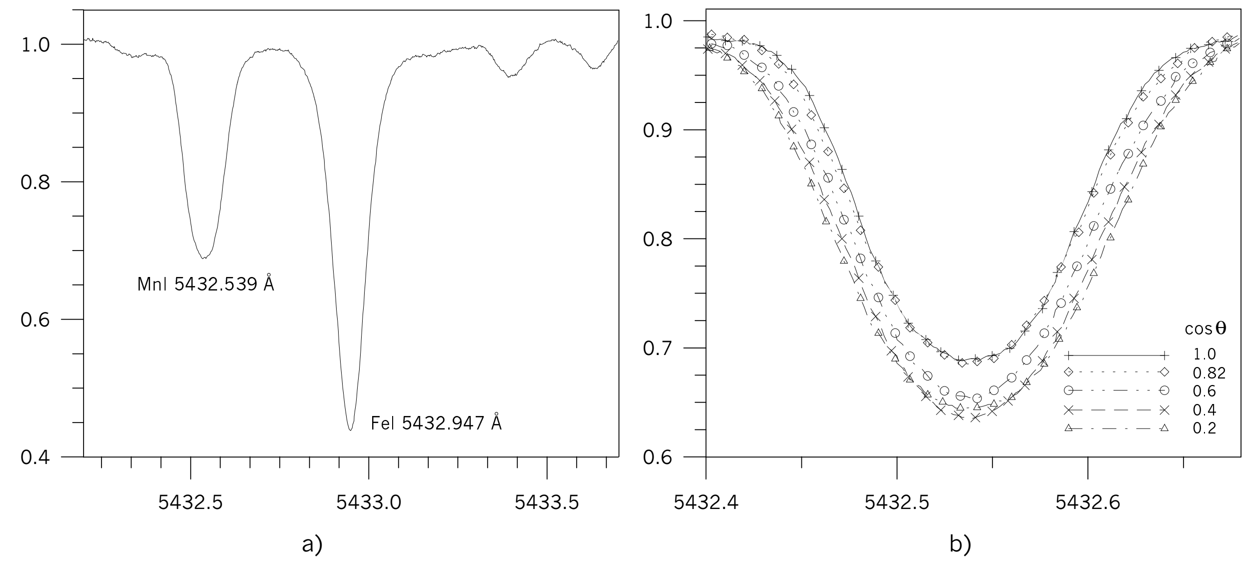

Figure 2. The average over solar disk spectrum near the Mn I 543.2 nm spectral line (a) and the Mn I 543.2 nm spectral line profiles for different heliocentric angles (b)

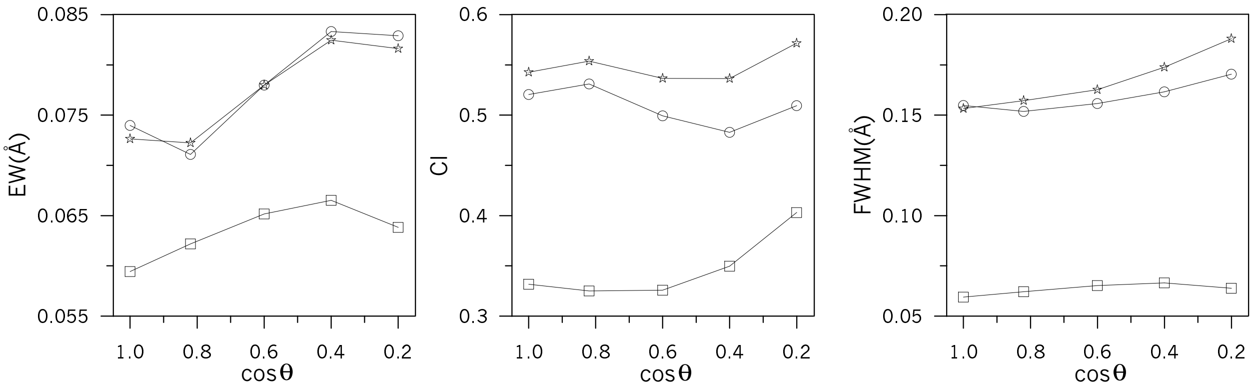

Figure 3. Center-to-limb variation of the observed (asterisks) and calculated (circles – with hyperfine components, squares – without hyperfine components) parameters of the Mn I 539.5 nm spectral line

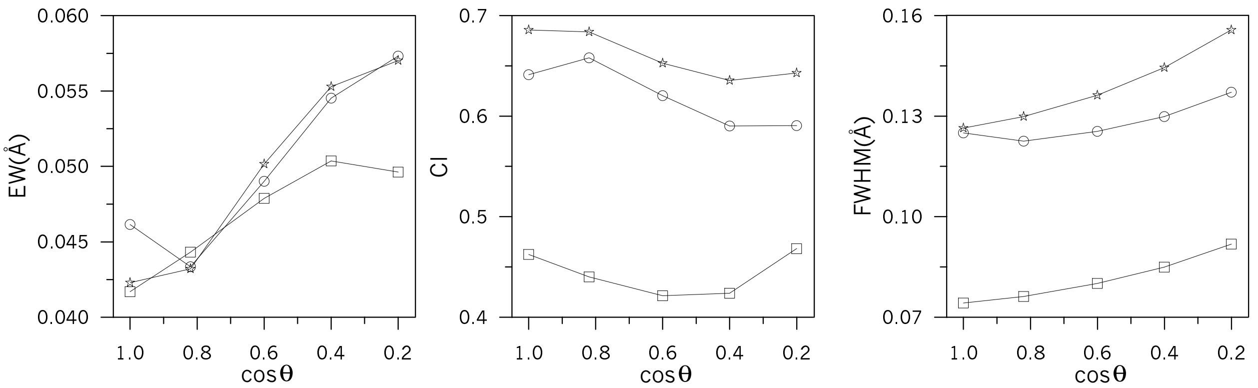

Figure 4. Center-to-limb variation of the observed and calculated (circles – with hyperfine components, squares – without hyperfine components) parameters of the Mn I 543.2 nm spectral line

ones if the hyperfine components are taken into account. There is systematic difference between calculated and observed *CI* and *FWHM*, but the variations of these parameters with the heliocentric angle are very similar. The differences are probably (partly) due to the influence of the instrumental profile, since the observed profiles are not corrected for it. On the other hand, the line profile parameters calculated without hyperfine components differ considerables from observed ones, and their changes with heliocentric angle behave very differently too. Therefore, we can conclude that the hyperfine structure essentially influence not only the shape of line profiles, but also its center-to-limb variation. The slight decrease of *EW* from $\cos\theta = 1$ to $\cos\theta = 0.82$ probably indicates that these lines are formed rather in deep than in high photospheric layers as it was found, *e.g.*, by Gurtovenko and Kostik (about 240 km, [9]). The hyperfine components could significantly influence on determination of manganese abundance. To confirm these conjectures further center-to-limb observations and calculations are planned to perform for these spectral lines.

Acknowledgements. Ministry of Science, Technology and Development of Serbia (contract N 1951) supported this work. One of the authors (I. Vince) acknowledges the support of the "Arany János Közalapítvány".

[1] *Livingston W.* Observations of Solar Spectral Irradiance Variations at Visible Wavelengths // Proceedings of the Workshop an the Solar Electromagnetic Radiation Study for Solar Cycle 22 / Ed. R. F. Donnelly.–1992.–P. 11–19.

[2] *Vince I., Erkapić S.* On the Chromospheric Behaviour of Photospheric Mn 539.47 nm Spectral Line // Int. Astron. Union Symp.–1998.–N 185.–P. 469–470.

[3] *Vince I., Erkapić S.* Influence of Temperature Gradient Changes on Solar Spectral Line Profile Parameters // Publ. Obs. Astron. Belgrade.–1993.–**44**.–P. 29–32.

[4] *Vince I., Vince O.* Temperature Sensitivity Determination of the Mn 539.47 nm Line from Solar-like Star Spectra Taken at Rozhen Observatory // Solar Researches in the South-Eastern European Countries: Present and Perspectives: Proc. Regional Meet. on Solar Physics / Eds G. Maris, M. Messerotti.–Éditions de l'Académie Roumaine.–2002.–P. 143–146.

[5] *Doyle J. G., Jevremović D., Short C. I., et al.* Solar Mn I 5432/5395 A line formation explained // Astron. and Astrophys.–2001.–**369**.–P. L13–L16.

[6] *Vince I., Gopasyuk O., Gopasyuk S., Vince O.* The observed Mn I 542.04 nm line profiles in solar plages // XXI Summer School and Intern. Symp. on the Physics of Ionized Gases / Eds M. K. Radović, M. S. Jovanović.–2002.–P. 562–565.

[7] *Vitas. N., Vince I., Vince O.* The Hyperfine Profile of the Mn I 539.47 nm Solar Spectral Line // Solar Researches in the South-Eastern European Countries: Present and Perspectives: Proc. Regional Meet. on Solar Physics / Eds G. Maris, M. Messerotti.–Éditions de l'Académie Roumaine.–2002.–P. 147–151.

[8] *Vitas. N., Vince O., Vince I.* The influence of Hyperfine Structure on the Mn I 543.25 nm Line Profile in Solar Spectrum // Kinematics and Physics of Celestial Bodies. Suppl. Ser.–2003.–N 4.–P. 142–146.

[9] *Гуртовенко Э. А., Костык Р. И.* Фраунгоферов спектр и система солнечных сил осцилляторов.–Киев: Наук. думка, 1989.