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NLTE Effects in formation of variable Mn I 539.4 nm line in solar spectrum

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Abstract. On the basis of NLTE profile calculations obtained by employing the radiative transfer code MULTI, the influence of the uncertainties of various parameters important in the formation of the photospheric Mn I 539.4 nm spectral line are discussed. Two cases are separately considered: with and without energy transfer between Mg II and Mn I. All calculations are performed with model atmospheres of Fontenla et al. (1999).

Key words. Sun: photosphere – Line: formation

1. Introduction

Among all lines in the solar spectrum, the most interesting are those that show either unexpected variation with time, or high sensitivity to various parameters of the atmosphere. When these lines are isolated in the spectrum they present an invaluable tool for plasma diagnostics. On the other side, a detailed explanation of their formation is a challenge for the theory.

Many of neutral manganese lines in solar spectrum are specific due to their wide hyperfine (**hf**) splitting. It is known that **hf** structure can have large effects on the abundances deduced from stellar spectra. Recently, it was also proposed that lines with pronounced **hf** structure could be used for measurements of the weak magnetic fields in the solar photosphere (López Ariste et al. 2002). On the other side, the weak resonant Mn I 539.4 nm line shows a relatively high variation of central depth and equivalent width anti-correlated with the solar activity (Livingston & Wallace (1987), Vince et al. (1988)). For the explanation of the described phenomena few hypothesis were proposed (Erkapić & Vince 1998). Doyle et al. (2001) have pointed out that an optical pumping mechanism of manganese lines by the strong emission from the core of Mg II k can produce the observed effect.

This paper is intended as a guide through various sources of uncertainty in the analysis of Mn I 539.4 nm line.

2. Theoretical line formation

For the calculation of line profiles in NLTE conditions the radiative transfer code MULTI (Carlsson 1986) was employed.

We used standard semi-empirical one-dimensional **atmospheric models** for quiet atmosphere, plage, network and sunspots constructed by Fontenla et al. (1999). These models were chosen to represent a consistent set of various features in solar atmosphere.

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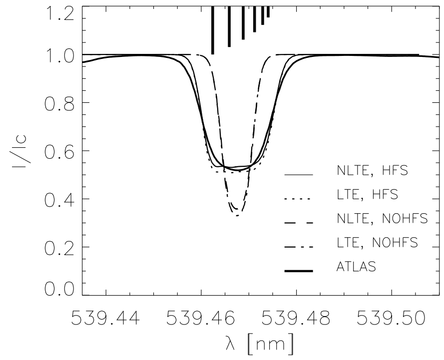

Fig. 1. Calculated profiles of Mn I 539.4 nm line with and without hf structure, in LTE and NLTE, compared with the observed spectrum. Lines on the top of the diagram present corresponding **hf** pattern.

After a detailed analysis of available atomic data the comprehensive **model atom** was constructed. It contains 64 energy levels plus continuum, and 161 bound-bound (the hyperfine splitting of 37 lines is explicitly taken into account) and 20 bound-free transitions. Many discrepancies exist between various sources of atomic data, and some data are missing, particularly measurements of photoionization cross-sections. An extensive description of the used model could be found in Vitas (2005).

Figure 1 shows calculated profiles of Mn I 539.4 nm in LTE and NLTE conditions, with and without **hf** structure. Oscillator strength was taken from Gurtovenko & Kostyk (1989), and **hf** splitting constants from Davis et al. (1971) (lower level) and Brodzinski et al. (1987) (upper level). Obviously, chosen data provide well agreement with observations (Delbouille et al. 1981), and NLTE calculation slightly raise the profile. Profiles calculated without **hf** do not fit observed spectrum at all.

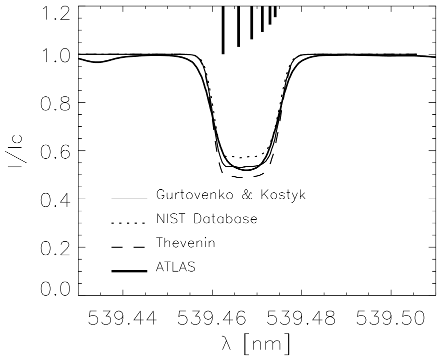

Fig. 2. The dependence of synthesized Mn I 539.4 nm profile on various values of oscillator strength.

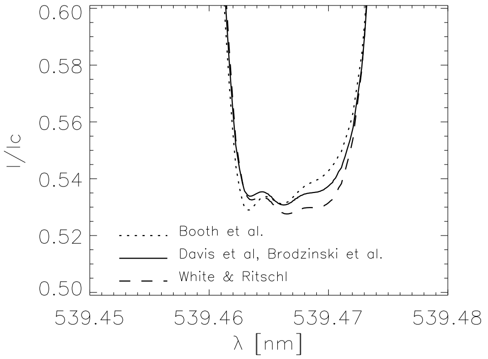

Fig. 3. The dependence of synthesized Mn I 539.4 nm profile on various data of **hf** splitting.

The dependencies of the calculated profile on various atomic data are shown in Figures 2 and 3. Oscillator strengths of Martin et al. (1988)[1] and Thévenin (1989) are in this model overestimated and underestimated, respectively. The influence of various **hf** data is almost negligible, particularly having in mind that different measurement techniques are used by Booth et al. (1983), White & Ritschl (1930), Davis et al. (1971) and Brodzinski et al. (1987), Fig.3.

The difference between abundance of manganese in the photosphere (5.39 ± 0.03) and in meteorites (5.53 ± 0.01) is noticeably higher than for the other elements of the iron group (Grevesse & Sauval 1998), Fig.4. This difference may be the consequence of neglecting the **hf** structure and NLTE mechanisms in solar Mn I abundance determination that contribute to the formation of selected lines.

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[1] NIST database, http://physics.nist.gov/

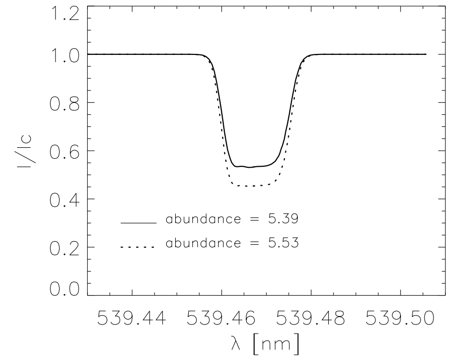

Fig. 4. Mn I 539.4 nm line calculated for two values of the solar abundance (5.39 in the photosphere, 5.53 in meteorites.)

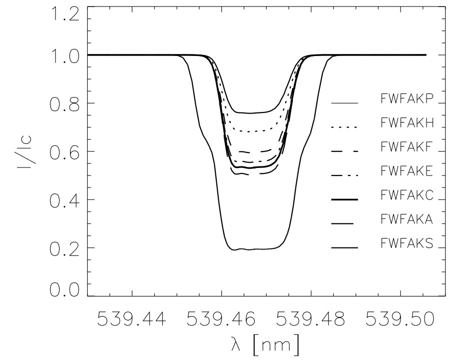

Fig. 5. Calculated profile of Mn I 539.4 nm in the seven models of Fontenla et al. (1999).

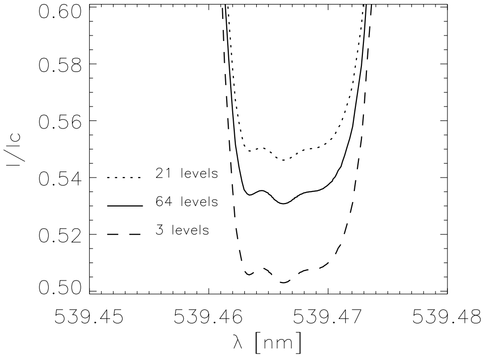

Fig. 6. The effect of various model atoms on the profile of Mn I 539.4 nm line.

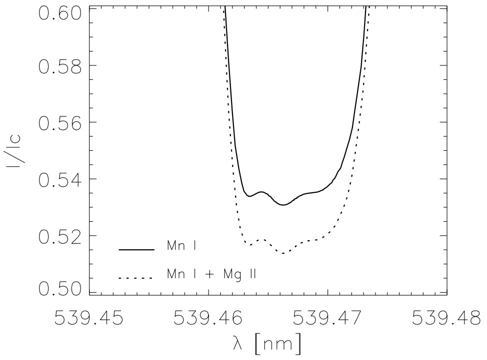

Fig. 7. After the inclusion of the optical pumping mechanism synthesized profile of Mn I 539.4 nm is deeper.

Line profiles of Mn I 539.4 nm calculated in various features in solar atmosphere are illustrated in Figure 5. Large differences between these line profiles are remarkable. Since the solar surface coverage by corresponding features varies with the time, remarkable differences between these line profiles could also cause the variation of integrated line profile.

Figure 6 shows the profiles of Mn I 539.4 nm obtained for three different model atoms. The simplest model (3 levels) gives deeper profile than the comprehensive one (64 levels). Contrary, the model that includes (UV1) multiplet and multiplets connected with its upper level y^6P^o (21 levels) raises the profile.

Finally, the effect of optical pumping of Mn I 539.4 nm by emission from the core of Mg II k is shown in Figure 7. Namely, in the quiet sun model, large absorption in Mg II drops down continuum for Mn I (UV1) transitions. That means lower flux, less (UV1) photons to be absorbed, larger population of Mn I ground level and more absorptions in other resonant lines (e.g. Mn I 539.4 nm). Anyhow, there may also be other reasons of unusual variation of this line, as it is proposed by Danilović & Vince (2005).

3. Conclusions

It seems that NLTE effects are not completely negligible in the formation of Mn I 539.4 nm line, although confirmation of this will require detailed analysis of the uncertainties in the used atomic data. In order to solve the problem more accurate atomic data for Mn I atoms must be calculated or measured and more realistic model of Mg II k & h lines formation should be used.

In that context, the analysis of the observed Mn I 539.4 nm variation is particularly difficult due to the large number of input parameters and their uncertainties

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