Is the Mn I 539.4 nm Variation with Activity Explained?

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Abstract. The photospheric Mn I 539.4 nm line in the solar spectrum shows unusual variability with the solar cycle in that its depth decreases with increasing activity. Doyle et al. (2001) claimed that this phenomenon is due to interlocking between the chromospheric Mg II h & k lines and an overlapping Mn I multiplet. In this contribution we test this hypothesis by synthesizing Mn I 539.4 nm line including these interlocking lines for a range of standard solar models and then combining resulting profiles without and with interlocking to emulate the full-disk profile variation. We find that the interlocking gives only a minor contribution; the largest one comes from different temperature stratifications in the photospheric layers of the various models.

1. Introduction

The Mn I 539.4 nm line in the solar spectrum is a photospheric one but it shows a significant variation with the 11-year activity cycle of the Sun (Livingston & Wallace 1987). Vince & Erkapić (1998) synthesized the line from different solar models but without finding the observed level of sensitivity to activity. However, at this meeting Solanki (2007) reported work by Danilović (2007) showing that LTE 1.5D modeling with an appropriate set of model atmospheres indeed mimics the observed behavior of the Mn line. In an earlier paper, Doyle et al. (2001) claimed that the unusual behavior is caused by coupling between the Mn I line and the Mg II k line. In this report we combine the two approaches by synthesizing the line for a range of standard solar models including interlocking with Mg II k.

2. Calculations

The Mn I 539.4 nm line is an intercombination transition from the Mn I ground state (multiplet 1, $a^6S \rightarrow z^5P^o$). The line is broadened considerably by hyperfine splitting. In the solar spectrum it appears as a relatively weak feature with an unusually broad core and visible substructure. It is mostly formed in the photosphere (Vitas 2005). The computed line strongly depends on the temperature stratification of the model atmosphere (Vitas & Vince 2005). Thackeray (1937) already pointed out that the Mn I 539.4 nm line shares the ground level with the UV1 multiplet of Mn I (279.482, 279.827, 280.106 nm, $a^6S \rightarrow y^5P^o$) which overlaps with the Mg II h & k lines (280.270 and 279.553 nm), see Fig. 1. The blue component of the UV1 multiplet is close to the emission core of Mg II k while the
Figure 1. A partial Grotrian diagram of Mg II and Mn I. Mn I multiplet 4 is expected to show behavior opposite to multiplet 1 (539.4, 543.2 nm). The transition $\alpha^6S \rightarrow \alpha^6D$ is forbidden. Its appearance as an emission line in the spectra of Mira’s was attributed to optical pumping between Mg II and Mn I already by Thackeray (1937).

other two components are located in the absorption dip between h&k. Doyle et al. (2001) suggested that (i) the low “local continuum” of the UV1 multiplet due to the absorption in Mg II k causes overpopulation of the Mn I ground level and increases the absorption coefficient in the Mn I 539.4 nm line, and that (ii) the increase of the emission in the Mg II k core with solar activity depopulates the ground level of Mn I, causing weakening of the Mn I line. The numerical results of Doyle et al. supported these conclusions qualitatively. However, they neglected the hyperfine structure of Mn I and assumed that the variation of the Mn I 539.4 nm line with activity can be modeled by varying a single 1D atmospheric model in somewhat arbitrary fashion, rather than using multiple models with appropriate filling factors.

To test the interlocking hypothesis we employ the Mn I model atom specified in Vitas (2005) and a Mg model atom supplied by Jevremović (2003). The set of 1D semi-empirical model atmospheres of Fontenla et al. (1999) was selected to represent six types of structures on the solar disk. The evolution of these features with the cycle is not considered here, but their average filling factors at solar minimum and maximum as specified by Fontenla et al. (1999) are taken into account. The radiative transfer computation was done with MULTI 2.2 (Carlsson, 1992). The radiation field in the Mg II h & k lines was computed first, and then it was used as a pumping radiation field in the lines of Mn I.

We find that the central depth $r$ of the computed Mn I 539.4 nm line profile depends strongly on the specific feature represented by the various models. In the hotter models, the line is weaker; in the cooler models it is stronger than in the quiet sun. Moreover, the effect of the Mg II k interlocking also depends on

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1The sunspot model is not considered because of its small filling factor (0.3 – 0.4% in the maximum of activity) and difficulties in Mg II h&k modeling with it.
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the selected model. In plage it produces depopulation of the Mn I ground level and weakens the Mn I 539.4 nm line. On the contrary, in the quiet sun model the effect is larger population of the ground level and a stronger line. The relative change of the Mn I central depth ($\delta = r'/r$) when the optical pumping is taken into account ($r'$) is given in Table 1 for each of the models. The table also specifies the average filling factors Fontenla et al. (1999).

<table>
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<tr>
<th>Model</th>
<th>Quiet Sun $(q)$</th>
<th>Active Sun</th>
<th>Active Sun</th>
<th>Active Sun</th>
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</table>

Table 1. Average filling factors of the models of Fontenla et al. (1999) and the computed relative change of the Mn I central depth ($\delta$) when the optical pumping is taken into account.

Linear combination of the parameters of the profiles computed from the different models with their corresponding filling factors describing quiet and active sun with large coverage by plage ($a \equiv a_2$) gives an estimate of the maximum line depth variation during the activity cycle, $\rho$:

$$\rho = \frac{r_{\text{active}}}{r_{\text{quiet}}} = \frac{\sum_m a_m r_m}{\sum_m q_m r_m} = 0.970,$$

where $r_m$ is the central depth in model $m$, $q_m$ and $a_m$ are the corresponding filling factors for quiet and active sun (Table 1), and $m \in \{A, C, E, F, H, P\}$. When the optical pumping mechanism is taken into account, its effect can be taken as a correction ($\delta$) to the calculated line profile, and this correction will depend on the model:

$$\rho_{\text{corr}} = \frac{r_{\text{corr,active}}}{r_{\text{corr,quiet}}} = \frac{\sum_m a_m \delta_m r_m}{\sum_m q_m \delta_m r_m} = 0.963.$$

If active sun with small coverage by plage is considered ($a \equiv a_1$), the estimated variation is smaller ($\rho = 0.981$, $\rho_{\text{corr}} = 0.975$). The overall effect of optical pumping to the variation of the Mn I 539.4 nm line is about 20% of the effect of the coverage variation.

An additional numerical experiment was designed to test the importance of the wavelength coincidence between the Mg II k emission peak and the blue component of the UV1 multiplet. Namely, if the hypothesis of Doyle et al. is valid, then the optical pumping should be more effective when blue UV1 component lies closer to the emission peak. To check this, we artificially changed the energy of the $y^6P^o$ level to change the wavelength of the blue UV1 component in the range between 279.466 and 279.681 nm. The calculations were repeated for each value. Practically no variation of the Mn I 539.4 nm line profile is produced...
in this way. We can conclude that the Mn I resonance multiplet 1 is actually insensitive to the photons emitted in the core of Mg II h & k.

3. Conclusions

Doyle et al. (2001) suggested that absorption in Mg II k as a quasi-continuum influences the Mn I populations. This is not likely to occur in the photosphere. On the other side, the variation of the Mn I 539.4 nm line with activity is more likely to be dominated by variable coverage of the solar disk by various activity features (Vince & Erkapić 1998, Danilović 2007). Our modeling supports this hypothesis and shows that the interlocking between the Mg II h & k lines and the UV1 multiplet of Mn I is insufficient to explain the observed variation. However, a much more detailed approach is necessary to confirm this conclusion. In particular, Mg II h & k should be synthesized including the effects of incomplete frequency redistribution.

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