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Solar Mn I 5432/5395 Å line formation explained

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Abstract. We present a solution for the long standing problem concerning the “chromospheric” behaviour of the Mn I 5395/5432 Å lines in the solar spectrum using multi-line/multi-species NLTE modelling. Using comprehensive spectral line formation modelling, we show that the Mn I lines are very sensitive to optical pumping in a transition which overlaps with Mg II k. It therefore follows that one has to be careful with the choice of lines as temperature indicators and for the determination of the Mn abundances although on the other hand, due to the formation process of these lines they may be useful as a solar and stellar activity diagnostic.

Key words. Mn I line formation – solar chromosphere – NLTE modelling – radiative interaction

1. Introduction

Observations of the Mn I 5394.7 Å line in the Sun began at Kitt Peak in 1979. The inclusion of this line with other photospheric lines was intended to provide additional long term information on temperature variations in the photosphere. However, it soon became apparent that the variation of this line was substantially different from other photospheric features. Livingston & Wallace (1987) showed that its central intensity and equivalent width were well correlated with the Ca II K 3933 Å intensity although no explanation was offered. In an analysis of the Mn I solar abundance, Booth et al. (1984) showed that both the 5432.55 and 5394.67 Å lines indicated ~20% higher abundances than several other Mn I lines. More recently Vince & Erkapić (1998) unsuccessfully tried to explain the formation of Mn I 5394.67 Å. Vince et al. (2000) has recently shown that the equivalent width and the central depth of the 5394.67 Å line changes with the strength of the magnetic field in plages.

In Fig. 1 we show observations of the Ca II K 3933 Å 1 Å index (defined as the equivalent width within 1 Å of the center of the line when the line is normalized to 3934.682 Å) and the Mn I 5394.67 Å line depth relative to a local 1-pt continuum (in this instance the flux at 5394.9108 Å is defined to be 1.0). There is an obvious correlation between the changes in the two lines. Although data exists from 1993 onwards, this is not included here as the Kitt Peak spectrograph underwent a grating change in late 1992.

In an analysis involving a very large flare on the RS CVn system II Peg, Doyle et al. (1992) showed that the Mn I 4031 Å line was partially filled-in during the flare while other photospheric features remained unaffected. Thus as in the earlier solar data this line acted more like a chromospheric feature, implying either the line was misidentified or that it is produced by fluorescence from some strong chromospheric line. Examples of other pumped lines are the O I 1304 Å triplet, pumped by Ly β (Skelton & Shine 1982) and Cl I 1351 Å pumped by C II 1335 Å (Shine 1983). Considering the Mn I system, Doyle et al. suggested that since the next upper level has a line at 2794.82 Å, which compares favorably with the wavelength of one of the members of the main Mg II resonance doublet, i.e. 2795.53 Å, that pumping was a real possibility. However, no calculations for the magnitude of this effect were presented. Here, we tackle this problem again, presenting a series of radiative transfer calculations involving

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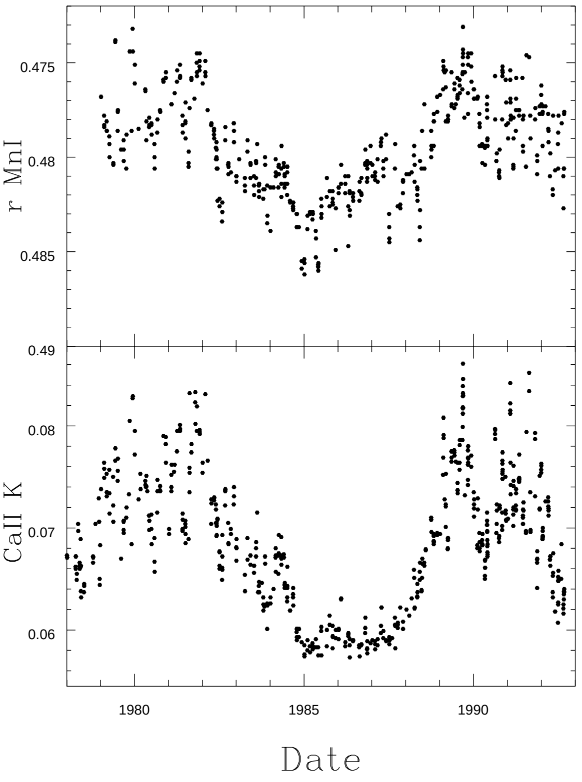

Fig. 1. Kitt Peak Ca II K 3933 Å and Mn I 5395 Å data from 1975 to 1992

PHOENIX (Hauschildt & Baron 1999; Allard et al. 2000), adopted for chromospheric modelling.

2. Modelling of Mn I spectrum

A sub-section of the term diagram of Mg II and Mn I for the levels involved in the radiative interaction is shown in Fig. 2. From this figure, it is clear that the population of the ground level ^{6}S and consequently the ^{8}P^0 level will be strongly influenced by the flux/radiative pumping by the Mg II k line.

To test the hypothesis of direct dependence of the Mn I 5432/5395 Å (1) line fluxes on the Mg II k line flux we calculated output fluxes for a small sample of schematic atmospheric models with solar effective temperature and different positions of the temperature minimum and transition region. The procedure of building these models is the same as described in Jevremović et al. (2000). We vary the position of the transition region from log $m_{\rm TR} = -5.0$ to -4.6 (m in g cm^{-2}) and the position of the temperature minimum, log m_0, from –2.5 to –1.5.

We solve simultaneously the equations of hydrostatic equilibrium, multi-level and multi-species statistical equilibrium and NLTE radiative transfer using the stellar atmosphere code PHOENIX (see i.e. Hauschildt et al. 1999; Short et al. 1999). We use the plane-parallel, static version of PHOENIX which has been adopted for use in chromospheric type of problems (Jevremović et al. 2001). For our particular task of investigating the Mg II/Mn I connection we use a model atom for Mg II with 30 levels in NLTE and Mn I with 60 levels. We also simultaneously solve the NLTE problem for Mg I and II, Ca I and II and Na I. Results of these calculations will be presented elsewhere.

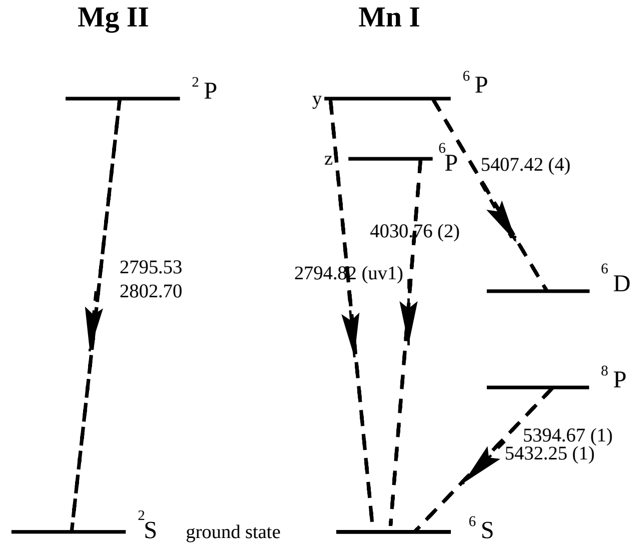

Fig. 2. A partial term diagram of Mg II and Mn I for the lines used in this study

3. Results

In Fig. 3, we present the results of our calculations for several Mn I lines formed in four different model atmospheres. These lines belong to multiplets 1, 2, uv1 and 4. We also plot Ca II K and Mg II k line profiles. All profiles of Mn I lines are normalized to the local continuum.

Multiplets 1 and 2 originate from the same lower level (ground) as uv1 and multiplet No. 4 shares the same upper level with the uv1 lines. Lines in multiplet No. 1 are very weak [log gf = –3.5 (5395 Å) and –3.8 (5432 Å)], multiplet No. 4 is also weak [log gf = –1.8 (5407 Å)], while multiplet 2 is fairly strong [log gf between –0.5 and –0.8 (4031–4034 Å)] and uv1 is strong [log gf between 0.24 and 0.53 (2795–2802 Å), Martin et al. (1988). From Fig. 3, it is clear that lines in all multiplets connected with the levels of multiplet uv1 depend strongly on the chromospheric signature.

To distinguish between the influence of radiative interaction between Mn I and Mg II and the atmospheric structure around the temperature minimum we plot in Fig. 4 three different situations using the same atmosphere (log m_0 = –2.5 and log $m_{\rm TR}$ = –5.0). The top row shows the line profiles without line blanketing and without consideration of Mg II. The middle row shows the influence of Mg II LTE opacities on the Mn I NLTE problem. In this case Mg II is not treated in detail, but only as a source of opacities. The bottom row shows line profiles in the full NLTE treatment of both Mn I and Mg II. The changes in the line intensities shown in the two lower panels are relatively small because we consider models with moderate activity levels. The changes in the flux in the near blue

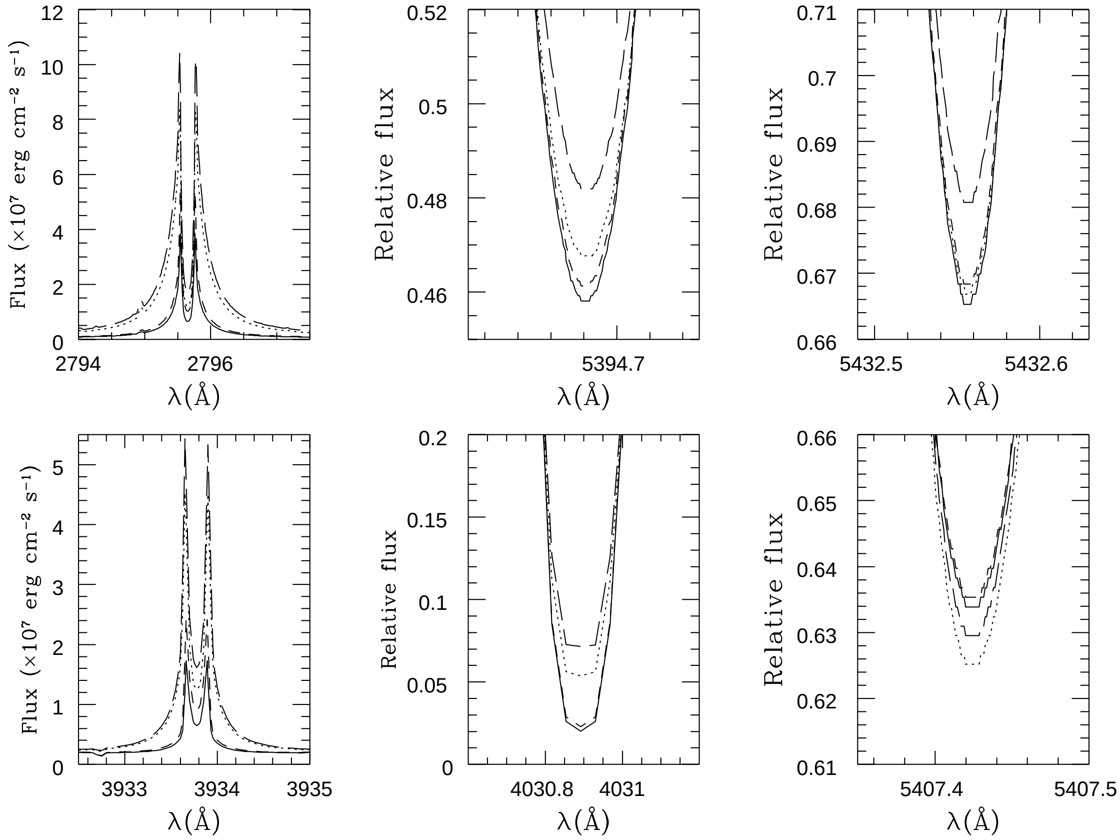

Fig. 3. Top row from left to right - line profiles Mg ii k with Mn i (uv1), Mn i 5395 Å (1) and 5432 Å (1). Bottom row — line profiles for Ca ii K 3933 Å, Mn i 4031 Å (2) and Mn i 5407 Å (4). Profiles shown are for atmospheres with (log m_0, log $m_{\rm TR}$) = (–2.5, –5.0) full line, (–2.5, –4.6) dashed line, (–1.5, –5.0) dotted line and (–1.5, –4.6) long-dashed line

wing of the Mg ii k line (where Mn i(uv1) is formed) are small and accordingly changes in the line flux of Mn i in this example are not large. If there was no interaction with Mg ii there would be no changes in the line profiles.

Because of the huge absorption in Mg ii, the local continuum for the Mn i uv1 lines changes. There is less flux and thus fewer photons to be absorbed and hence the ground level is consequently more populated. The resulting increase of the absorption coefficient occurs also in the weaker Mn i multiplets.

However, if the core of Mg ii k is in strong emission, then the ground level of Mn i is de-populated by Mg ii pumping. This effect is seen in the figures as the weakening of absorption in lines originating from the ground level. On the other hand, because of overpopulation of the upper level there is going to be fluorescence in the lines originating from this level – i.e. excess emission will be seen as a filling-in of the line profile. Because of the known correlation between Mg ii k and Ca ii K (also seen in Fig. 3), the link between Ca ii K and Mn i 5395 Å is obvious.

4. Conclusion

We have demonstrated the existence of a direct link between lines of Mn i sharing the same levels as lines in multiplet uv1, which has a strong interaction with the Mg ii k line. This link therefore solves the long standing “history” concerning the chromospheric behaviour of Mn i 5395 Å. The 4031 Å multiplet also showed major changes so in the case of flares we expect this multiplet to fill-in as observed by Doyle et al. (1992). Due to the formation process of these lines they may be useful as a solar and stellar activity diagnostic.

Some authors have suggested the Mn i 5395 Å line can be used as a temperature indicator for the Sun and solar-like stars (Elste 1986). The present calculations confirm that the 5395 Å line is more suitable as an optical replacement for the measurement of the Mg ii k line flux. Furthermore, as noted by Booth et al. (1984), one has to be careful with choice of Mn i lines suitable for abundance analysis and bear in mind the radiative interaction with Mg ii k.

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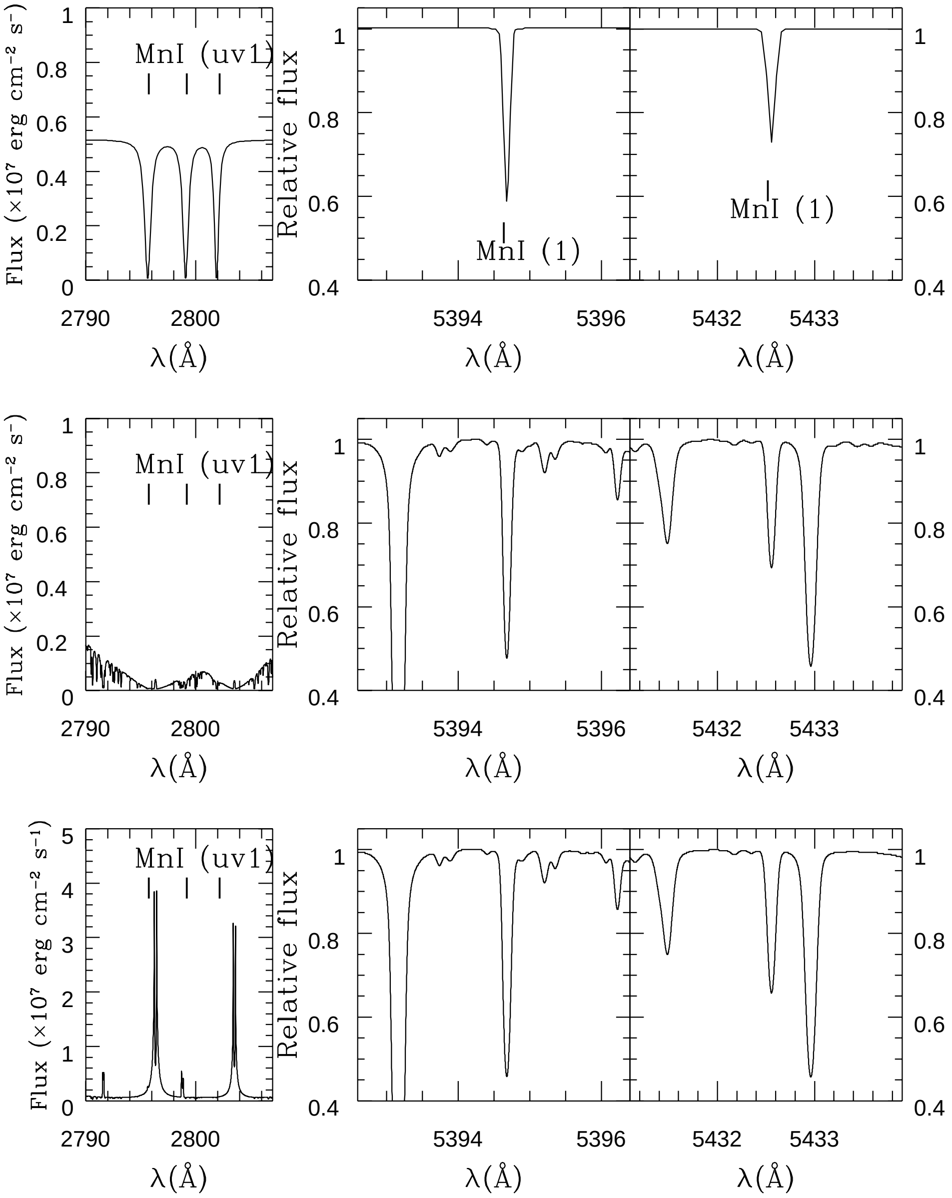

Fig. 4. The top two panels show the results of NLTE calculation for Mn I without any interaction with Mg II and no line blanketing. In the middle row, we show the results of NLTE Mn I obtained with Mg II LTE line opacities included (but not treated explicitly as a line transfer) and bottom row the results when both Mn I and Mg II are treated in NLTE. The atmosphere has log $m_0 = –2.5$ and log $m_{\mathrm{TR}} = –5.0$

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