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Magnetic source of the solar cycle variation of the Mn I 539.4 nm line

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Abstract. As a part of the long term program at KPNO, the Mn I 539.4 nm line has been observed for nearly three solar cycles using the McMath telescope and the 13.5 m spectrograph in double pass mode. These full-disk spectrophotometric observations revealed an unusually large amplitude change of its parameters over the solar cycle and its correlation with Ca II K intensity. One of the proposed explanations for this phenomenon is the optical pumping by the Mg II k line. With this work we would like to show that this may not be the main mechanism behind the change. We reconstructed the changes of the line parameters using a model that takes into account only changes of the daily surface distributions of magnetic field. This model has already been used to successfully model total solar irradiance. We now apply it for modelling the Mn I line, as well as its neighboring Fe I line using exactly the same value of the free parameter as used for the reconstruction of total solar irradiance. We reproduce well the Mn I and Fe I line changes over the cycle purely with LTE modelling. This indicates that optical pumping of the Mn I line by Mg II k is not the main cause of its solar cycle change and sets an independent constraint on solar irradiance models.

1 Introduction

The Mn I 539.47 nm line is interesting for several reasons. The hyperfine broadening, due to interaction of the electronic shell with the nuclear spin, makes it insensitive to non-thermal motions and hence more sensitive to the temperature in the photosphere (Elste & Teske 1978; Elste 1987). Observations show that the line becomes stronger in sunspots and weaker in plage and network (Andriyenko 2004; Vince et al. 2005a; Malanushenko et al. 2004; Vince et al. 2005b). Although calculations confirm its photospheric origin (Gurtovenko & Kostyk 1989; Vitas 2005), the 'Sun-as-a-star' observations (Livingston & Wallace 1987; Livingston 1992) exhibit a significant cyclic dependence, not typical for photospheric lines. As a possible explanation Doyle et al. (2001) proposed optical pumping by Mg II k, which could be the reason why this Mn line mimics the change seen in Mg II k. On the other hand, this high correlation may be a consequence of the common source of change in both cases: bright magnetic elements - faculae and network (Danilovic & Vince 2005). This work aims to test the latter hypothesis.

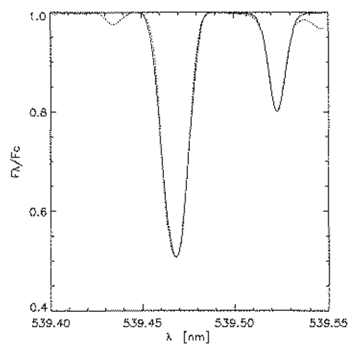

Figure 1. Comparison of Mn I 539.47 and Fe I 539.52 nm line profiles observed on May 19th 1999 (dotted) with the synthesized ones (solid).

2 Observations and modelling

Observed 'Sun-as-a-star' spectra obtained with the Kitt Peak 13.5 m scanning spectrometer in double pass mode are used (Livingston & Wallace 1987). The first set of observations was taken from 1979 to 1992, after which the grating was changed. Implementation of the new, larger grating eliminated the loss of light from the Sun's poles. This introduced a 'jump' in equivalent width (EW) and central depth (CD) of lines. There followed an experimental period with the new grating and the changing of instrumental parameters. This lasted till 1996 when the system was fixed and observations are performed regularly again (Penza et al. 2006).

To reconstruct the time variability of the Mn I line, the SATIRE (Spectral And Total Irradiance Reconstruction) model has been used (Fligge et al. 2000; Krivova et al. 2003; Wenzler et al. 2005, 2006). This model gave excellent agreement of calculated and observed total solar irradiance (TSI) on both short and long time scales in the period of 1978 to 2003. In the model, the position and flux density of magnetic features are extracted from full-disk magnetograms and continuum images. These magnetic features are classified as either sunspot or faculae. Every feature is represented by a plane-parallel model atmosphere with a unique temperature stratification (Unruh et al. 1999). To account for the unresolved magnetic elements, the model introduces a filling factor parameter, which describes the fractional coverage of a pixel by a facular model, which linearly increases with magnetogram signal. The limiting value for which the pixel is completely covered by faculae is a free parameter. We stress that in the present analysis exactly the same value of this free parameter has been used as employed in earlier studies to model total solar irradiance change for the same period.

Time independent emergent intensities of the Mn I line and the neighboring Fe I line are calculated for each model atmosphere for various heliocentric angles in LTE using the SPINOR code (Frutiger et al. 2000). No magnetic field is introduced in the calculations. The hyperfine structure of the Mn I line is included as blends with displacement calculated using the hyperfine constants from Davis et al. (1971) and relative intensities of the components from Condon & Shortley (1963). Components, that are closely spaced with respect to the total splitting, have been combined to reduce the computing effort.

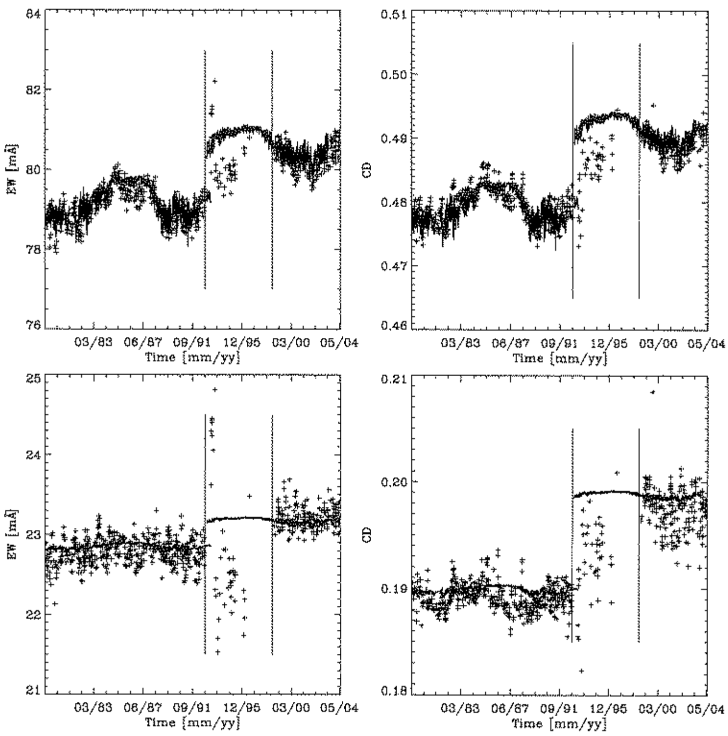

Figure 2. Equivalent widths (left) and central depths (right) of the Mn I 539.47 nm (up) and its neighboring Fe I 539.52 nm line (down) extracted from KPNO observations (crosses) and calculated using our model (solid line). Experimental period is bounded by vertical solid lines.

3 Results

In order to be consistent with the instrument setup, in the period before 1992 the flux is computed neglecting contributions from the poles, which were missed by the old grating. By fitting the line parameters for several days during cycle minimum we estimated what portion of the disk is missed. The obtained fit of the synthesized to the observed spectrum of Mn and its neighboring Fe line is shown in Fig. 1. The whole interval covered by the observations is given in Fig. 2. Vertical solid lines mark the period during which the instrumental setup experimentation lasted. Overplotted on the data are the modelled values, which also display the jump in CD of both lines because of different influence of the rotation on the line profiles before and after 1992. The behavior of both lines is well reproduced. Correlation coefficients for EW and CD of the Mn I 539.47 line are 0.94 and 0.96, respectively.

4 Conclusion

The solar cycle variation of Mn I 539.47 nm line parameters have been modelled in LTE taking into account only changes of the surface distribution of the solar magnetic features. As the solar disk coverage by bright magnetic features increases toward solar cycle maximum, the Mn I line becomes weaker in the 'Sun-as-a-star' spectrum. In this way it mimics the behavior of Ca II K and Mg II k lines which are well known plage/faculae indicators. Good correlation with observations is obtained without taking into account the influence of the Mg II k line. This puts the optical pumping hypothesis in the background. Although energetic transfer between Mn I and Mg II exists, we do not expect it to be significant for the solar cyclic variations of the Mn I 539.47 nm line.

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