Astronomy & Astrophysics Indonesia
Proceedings Conference of the Indonesian Astronomical Society (HAI), 29–31 October 2009
Editor: Premana W. Premadi

The solar activity sensitivity of Mn I lines

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Abstract. The Mn I 5394.7 Å line is the only spectral line originating in the solar photosphere for which it has been established that it tracks solar magnetic activity in its line-center brightness in the disk-averaged "Sun-as-a-star" solar irradiance spectrum. This activity sensitivity has been attributed to spectral interlocking to the chromospheric Mg II h & k lines in the ultraviolet via overlap with the Mn I resonance multiplet. However, this explanation does not hold when one accounts properly for partial frequency redistribution in the Mg II h & k lines. A detailed radiation-magnetohydrodynamics simulation shows that the reason for the activity sensitivity of Mn I 5394.7 Å and other Mn I lines is rather that all other photospheric lines show the non-magnetic granulation too bright. The Mn I lines do not suffer such brightening because their cores are widened by large hyperfine structure, so that they are less sensitive to the granular Dopplershifts. This is a purely photospheric effect.

Keywords. Sun: activity, Sun: photosphere, Sun: chromosphere, Sun: faculae, plages.

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1. Introduction

The sensitivity to solar activity of the solar Mn I 5394.7 Å line was established in extensive observations of this line by Livingston and coworkers and later also by Vince and coworkers (Livingston & Wallace 1987; Vince & Erkapic 1998; Danilovic & Vince 2004, 2005; Malanushenko et al. 2004; Danilovic et al. 2005; Vince et al. 2005a, 2005b; Livingston et al. 2007).

Livingston's inclusion of the Mn I 5394.7 Å line in his long-term full-disk "Sun-as-a-star" line profile monitoring from 1979 onwards was prompted by Elste, who suggested that their large hyperfine structure makes the Mn I lines less sensitive to the questionable microturbulence parameter than other ground-state neutral-metal lines that may serve as temperature diagnostic (Elste & Teske 1978; Elste 1987).

Livingston then found that this line is the only photospheric line in his full-disk monitoring that exhibits appreciable variation with global activity, in good concert with the Ca II K full-disk intensity variation. Its equivalent width in the irradiance spectrum varies by up to 2% (Livingston & Wallace 1987). Figure 1 illustrates his findings. It raises the question why Mn I 5394.7 Å displays such sensitivity to activity while most if not all other photospheric lines do not.

2. Incorrect explanation: pumping by Mg II h & k

Doyle et al. (2001) explained the sensitivity of Mn I 5394.7 Å to activity through optical pumping by the chromospheric cores of Mg II h & k. Thackeray (1937) had already pointed out that the violet wing of Mg II k (line center at 2795.53 Å) overlaps with Mn I 2794.82 Å and so may produce optical pumping of that and other Mn I lines in stellar spectra. Doyle et al. (2001) used NLTE computations to show that solar Mn I lines are also sensitive

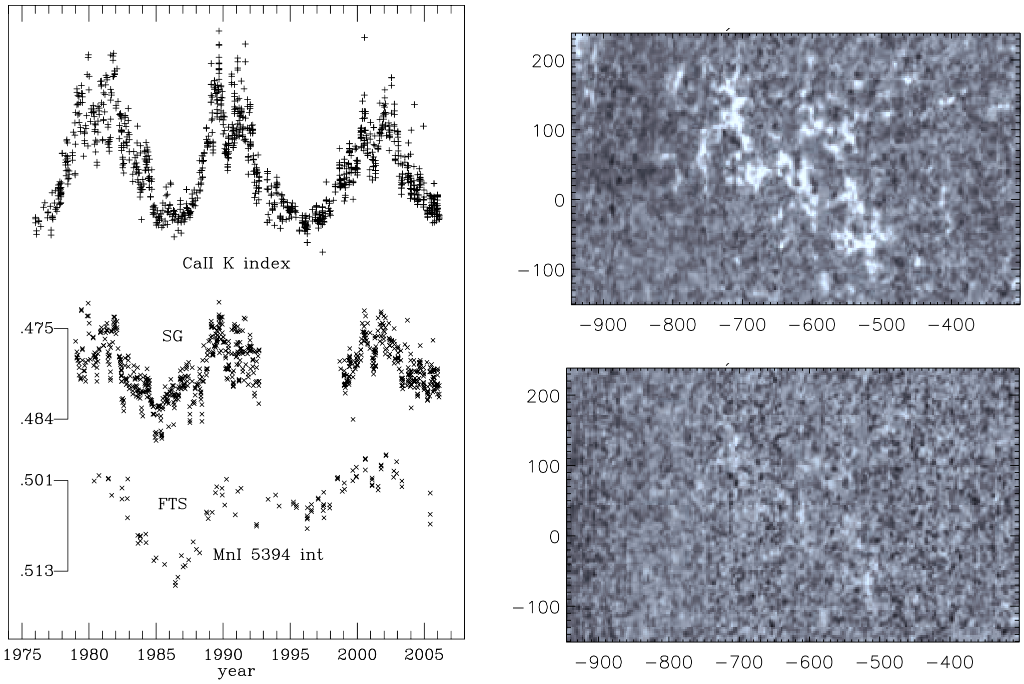

Figure 1. Left: Figure 16 of Livingston et al. (2007), showing the concurrent variation with solar activity of the full-disk Ca II K index (1 Å passband selecting the line core) and the central line depth (plotted upside-down) of Mn I 5394.7 Å, measured with the spectrograph (SG) and Fourier Transform Spectrometer (FTS) at the McMath-Pierce telescope at Kitt Peak during the past decades. The Mn I line brightens (weakens) significantly at larger activity. Right: parts of Figure 1 of Malanushenko et al. (2004), showing spectroheliogram scans across a plage region made at the centers of Mn I 5394.7 Å and the weak neighboring Fe I 5395.2 Å line. The Mn I line (upper image) brightens much more in plage than the Fe I line (lower image).

to optical pumping through this overlap coincidence. The demonstration consisted of computing Mn I profiles for different solar chromosphere models with and without taking Mg II h & k into account. Appreciable variation of the Mn I lines was found and attributed to such spectral interlocking.

Doyle et al. (2001) gave their paper the title "*Solar Mn I 5432/5395 Å line formation explained*". However, last year Nikola Vitas, a graduate student at Utrecht from the Mn I-interested Belgrade school of I. Vince, convinced me that perhaps it might not be the explanation. At closer inspection I indeed found that the claim is untenable. This is demonstrated by Figure 2 which combines the pioneering Mg II h & k observations of Lemaire & Skumanich (1973) with the pioneering modeling of Milkey & Mihalas (1974). The observation at left shows that the Mg II k peak never extends as far as the Mn I overlap line, while it did in the modeling of Doyle et al. (2001). Their computed peaks had extended wings that rose to large intensity for more pronounced model chromospheres, also covering the Mn I blend. The observed wings do not, so something must have been wrong in the computation. The diagram at right shows that the error was the assumption of complete redistribution, rather than evaluating the Mg II k line source function taking coherent scattering into account. Such scattering makes the radiation fields in the wings independent from those in the core and lets them decouple from the Planck function already in the photosphere. The resulting wing intensities are overestimated considerably

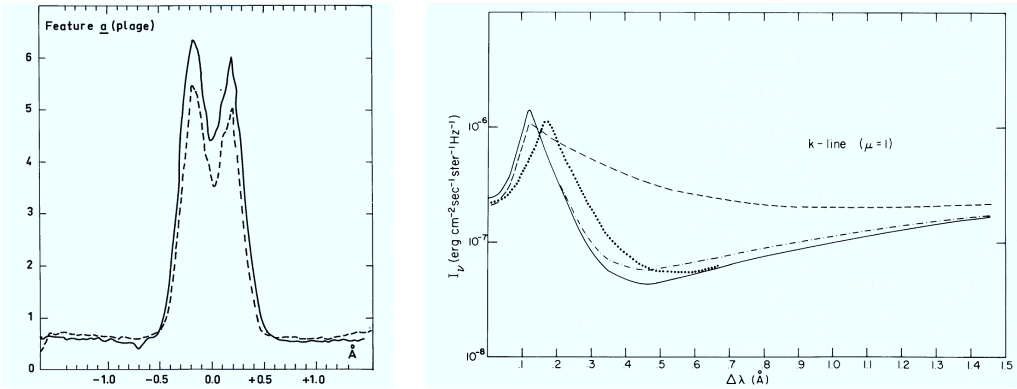

Figure 2. Left: observed Mg II h & k profiles from Lemaire & Skumanich (1973) for a plage with maximal h & k peaks. Solid: Mg II k; dashed: Mg II h. The overlapping Mn I line is the small dip at $\Delta\lambda = -0.7$ Å. Right: computed Mg II k profiles (only the red half) from Milkey & Mihalas (1974). Dashed: complete redistribution. Solid: partial redistribution. Other curves: partial redistribution with other parameter choices.

when complete redistribution is assumed. This simplification is about the worst it can get for these particular line wings, as shown by Milkey & Mihalas (1974).

I now have to make a confession. After this closer inspection I concluded that the referee to Doyle et al. (2001) had failed badly in passing this striking disagreement with these pioneering papers from 25 years before. To my consternation, I then found that I had been the referee myself. I knew the papers of Lemaire & Skumanich (1973) and Milkey & Mihalas (1974) well, so I now wonder why I did not retrieve them and check the profiles of Doyle et al. (2001) against theirs. Oops…

3. Correct explanation: insensitivity to Doppler brightening

Nikola Vitas had become a graduate student at Utrecht to work with Alexander Vögler, my successor there, on spectral-line synthesis on output from Alexander's 3D MHD simulations with his MURaM code (Vögler & Schüssler 2003; Vögler 2004; Vögler et al. 2005), which is highly suited to synthesize photospheric lines including solar granulation, the surface representation of solar convection, and the small-scale magnetic concentrations that constitute plage in solar active regions. Synthesis of the Mn I line required Stokes profile evaluation including hyperfine structure, for which we contacted Bartolomeo Viticchiè at Rome who had been synthesizing Stokes Mn I profiles in his thesis work (Sánchez Almeida et al. 2008). And so we teamed up to find the explanation how Mn I 5394.7 Å can sense activity without chromospheric pumping. We did so by performing spectral line synthesis for the Mn I line and for the neighboring weak Fe I line used in the lower-right image in Figure 1, using a snapshot cube from a MURaM simulation containing realistic granulation with intergranular magnetic concentrations that had developed in the simulation from convective squeezing of the homogeneous start-up field.

Our results are extensively described in Vitas et al. (2009) and are here summarized in Figure 3. The synthetic images in the second row show granules bright in the continuum (first column), less bright in Fe I 5395.2 Å line center (second column), and dark in Mn I 5394.7 Å line center (third column). The magnetic concentrations, which preferentially occur in the vertices of intergranular lanes, appear about equally bright at the three wavelengths.

The brightness enhancements of magnetic concentrations was explained long ago by

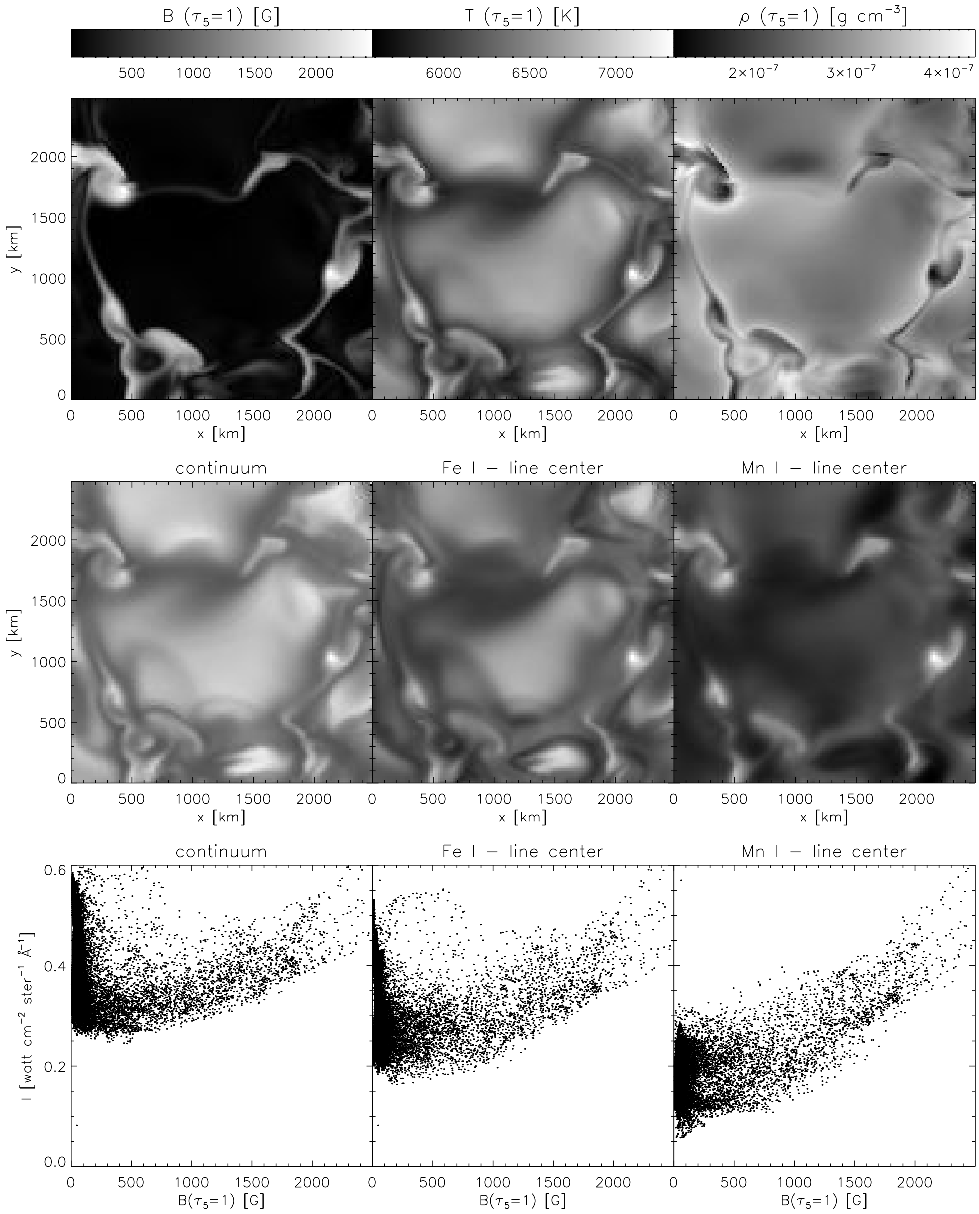

Figure 3. Synthesis of Mn I 5394.7 Å and Fe I 5395.2 Å with the MURaM MHD code. Upper row: magnetic field strength, temperature, and gas density at the $\tau_5 = 1$ surface where the continuum radiation at $\lambda = 5000$ Å emerges. The simulation includes a large granule at the center of the volume, dark intergranular lanes, and intergranular magnetic fields. The first panel shows that the field reaches its highest values in small patches at intergranular vertices: these “magnetic concentrations” closely resemble “magnetic fluxtubes” as in Figure 4. Second row: synthetic images in the continuum and the line centers of Fe I 5395.2 Å and Mn I 5394.7 Å. Third row: scatter plots of the intensity in the continuum, the Fe I line, and the Mn I line against the magnetic field strength. The images in the second row show that the granules appear darkest in the Mn I line, whereas the strongest magnetic concentrations are equally bright at all three wavelengths. The scatter plots in the bottom row show hook forms in the first two cases, in which the black cloud of non-magnetic granulation pixels at left in each panel extends upward to similar brightness as the pixels with the largest field. The last diagram shows no hook shape.

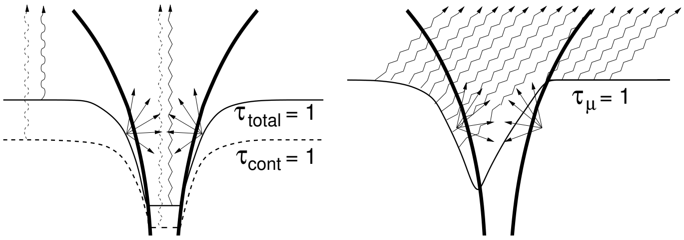

Figure 4. Schematic brightening in a magnetic concentration, portrayed here as a vertical cut through an idealized, flaring fluxtube (thick curves) containing strong field, embedded in a field--free quiet photosphere. *Left*: in radial viewing the Wilson depression due to magnetic-pressure evacuation deepens the photon escape layer characterized as $\tau = 1$ surface to well below the outside surface. The fluxtube gas is much cooler there than in the subsurface surroundings, due to suppressed convection, but it is hotter than the outside photon escape layer due to its large depth and hot-wall irradiation. The correspondingly larger degree of ionization of low-ionization species as Mn I and Fe I weakens their lines, causing a yet larger effective Wilson depression in them and so producing larger brightness enhancement than in the continuum. *Right*: In near-limb viewing the same lack of opacity along the slanted line of sight causes deeper, facular "bright-stalk" sampling of hot granules behind magnetic concentrations. From Rutten (1999).

Henk Spruit in his thesis (Spruit 1977) following a suggestion by Kees Zwaan in his thesis (Zwaan 1965). Figure 4 gives a cartoon explanation following their similar schematic in Spruit (1976), which later inspired the magnetostatic fluxtube modeling of e.g. Solanki (1986), Solanki & Steenbock (1988), and Solanki & Brigljevic (1992).

Our Mn I paper analyzes this mechanism in much detail, showing how the Mn I and Fe I line are depleted in such magnetic concentrations, but the upshot is clear from the bottom panels of Figure 3: in the strongest-field locations (to the right in each scatter diagram), both the Fe I line and the Mn I line vanish so that the concentration is marked by "bright points" nearly as bright as they appear in the continuum.

What differs between the two lines in Figure 3 is the darkness of the non-magnetic granulation in the Mn I line. For the continuum the granulation (scatter cloud at left in each diagram) reaches the same brightness as the brightest magnetic concentrations. In the Fe I line the bright granule centers are darker (Fe I 5395.2 Å being an absorption line, as all others from the photosphere), but still with an upward tail forming a hook pattern in the scatter diagram. Such a tail is lacking for Mn I 5394.7 Å, in which also the granule centers are relatively dark.

These synthetic images and scatter diagrams suggest that solar plage, a dense assembly of small magnetic concentrations similar to the few in this simulation, is not particularly bright in the Mn I line but that the non-magnetic granulation outside such regions is imaged brighter in Fe I 5395.2 Å and similar lines – meaning all other photospheric lines. Therefore, the question becomes again what is particular about Mn I lines. The answer, demonstrated at length in Vitas et al. (2009), is the same as what triggered Elste's suggestion to Livingston that triggered this whole Mn I story: Mn I lines have larger hyperfine-structure broadening than any other lines in the solar spectrum. The Mn I 5394.7 Å line therefore has a boxy core, wider than the pointed Gaussian cores that other lines obtain from thermal and turbulent broadening and give them larger sensitivity to Dopplershifts. For the other lines, the updrafts in hot granules and downdrafts in descending intergranular lanes cause overall Doppler brightening because the line-center opacity does not sample the shifted peak of the extinction profile, neither in the ascending granules nor in the descending intergranular lanes. Thus, "normal" photospheric lines are brighter than they should be, whereas the boxy Mn I lines portray the brightness temperatures in the granulation without such Doppler contamination. The conclusion is that plage appears relatively bright in Mn I 5394.7 Å only because the non-magnetic granulation outside plage appears too bright in all other photospheric lines.

However, during my presentation at this conference I noted that the granulation appears similarly dark in both scans in Figure 1, not darker in the Mn I line. By reanalyzing the data of Malanushenko et al. (2004) I found the cause of this apparent discrepancy: they plotted reversed line depths normalized by the mean, which is dominated by the granulation (and with a large zero offset to boost the contrast). Plotting their data as intensities scaled to the plage indeed darkens the granulation in the Mn I line.

The upshot of this story is that the apparent activity sensitivity of the Mn I 5394.7 Å line is due to its hyperfine structure, which makes it less sensitive to the Doppler brightening that affects all other photospheric lines. It has nothing to do with the chromosphere and therefore is not a diagnostic of chromospheric activity modulation.

The morals of this story are clear: *(i)*, when one referees a paper one must always check older work that the authors may not have looked at, and *(ii)*, when some particular feature seems special, be sure that not, instead, all common features are special.

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