Line Bisector Variability in the Sun as a Star

Mark Giampapa[1], **Luca Bertello**[1] **& Alexei Pevtsov**[1]

[1]*National Solar Observatory, Tucson, Arizona, USA 85726-6732*

Abstract. We utilize spectra obtained with the Integrated Sunlight Spectrometer (ISS) instrument of the NSO SOLIS facility on Kitt Peak, AZ to perform a preliminary study of the variability of line asymmetries in the Mn I line at 539.5 nm and the nearby Fe I line at 539.3 nm, respectively. We derive the line bisector for these photospheric features from daily spectra of the Sun as a star acquired since January 2007, and characterize the variability of a measure of bisector amplitude with the solar cycle. A simple two-component model of the solar magnetic field is investigated as a possible origin for the variation in line depth with time of the magnetically sensitive Mn I feature.

1. Introduction

The intrinsic asymmetryin spectral lines in the Sun and late-type stars arises from the velocity-brightness correlation between hotter and brighter upward (blueshifted) moving granules and downward (redshifted) flowing plasma in the intergranular lanes (Gray 1988). Thus, natural line asymmetries are a diagnostic of the nature of global velocity fields in the solar-stellar atmosphere as seen in spatially integrated spectra.

We utilize spectra obtained with the Integrated Sunlight Spectrometer (ISS)– an instrument of the NSO SOLIS(*Synoptic Long-term Investigation of the Sun*) facility on Kitt Peak, Arizona – to conduct a preliminary investigation of the variability of line asymmetries in selected solar photospheric lines since 2007. The SOLIS facility with its suite of instruments is described by Keller et al. (2003). Additional details about ISS observations are given by Bertello et al. (2011). The ISS spectra discussed herein were calibrated according to procedures described by Pevtsov et al. (2014). We display in Fig. 1 spectra obtained in the region of interest during the extended solar minimum in 2009 and the current rise toward the maximum of Cycle 24 in 2014. Also shown for reference is the time series of the 1 Å index in the core of the Ca II K line. We adopt the line bisectoras a measure of the line asymmetryand calculate its velocity span or amplitude, in the Mn I line at 539.47 nm and the nearby Fe I feature at 539.32 nm, respectively. We discuss general features of the

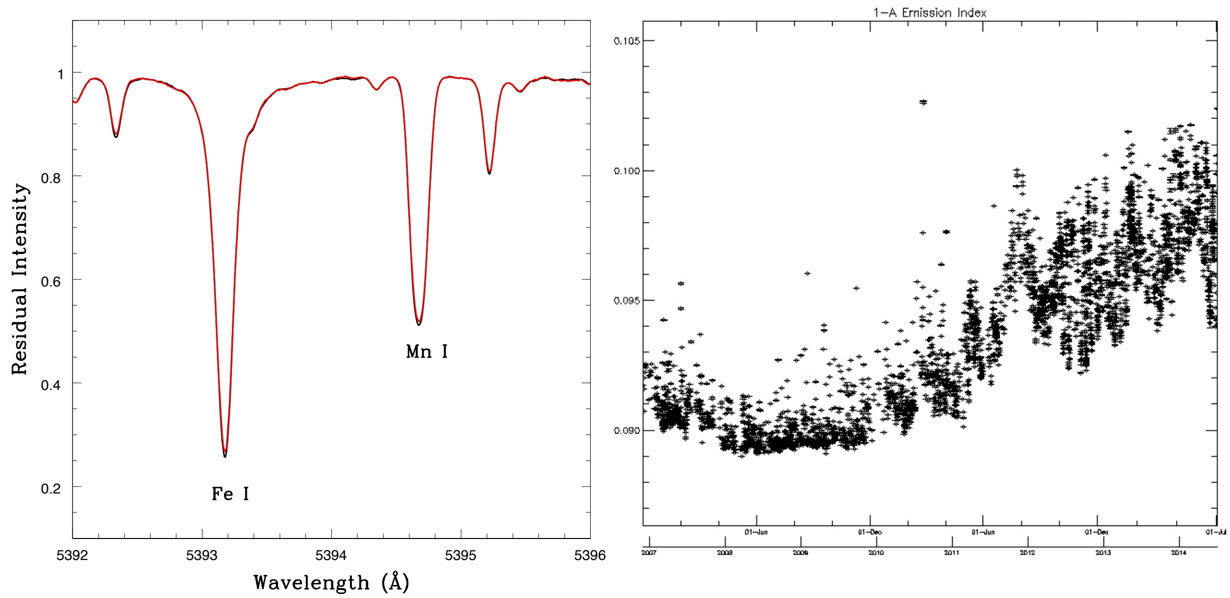

Figure .1: The spectral region of the Fe I and Mn I lines (*left*). The spectrum is from 3 May 2009 (solid black line). Overplotted (dashed red line) is the spectrum from 3 May 2014. Note the slight filling in of the line cores in the spectrum from 2014 (dashed-red). The Ca *II* K time series for the 1-Å core emission index in the Sun observed as a star is displayed for reference (*right*). The spectral resolution is about R = 300,000

variability of the profiles with the solar cycleof activity We also refer the reader to Bertello et al. (2014; these Proceedings) for a complementary discussion of variations in photospheric line parameters in the Sun as a star.

2. Line Bisector Construction

We followed the approach described by Povich et al. (2001) in their analysis of stellar line bisectors in the spectra of hosts of exoplanet systems. Specifically, we start with the point nearest the central wavelength position and then step up the blue side of the profile point by point. We determine the line center position through a spline fit to the (relatively broad) core. The line bisector was derived by using points on the blue side of the profile without any interpolation and performing a linear interpolation between wavelength positions on the red side at the same relative intensity. We then determined the midpoint of the corresponding segment with the bisector constructed by connecting the midpoints of all the line segments. This procedure typically yielded a bisector consisting of 21 points in these high-resolution solar spectra.

Examples of line bisectors for the Mn I line and the Fe I feature displayed in Fig. 1, respectively, are given in Fig. 2. Bisectors of both lines exhibit the characteristic "C-shape arising from the velocity-brightness correlation of granular motions. However, the Mn I bisector is characterized by a complex structure with less of an overall C-shape in 2014 compared to that from 2009. Livingston et al. (1999) have attributed the reduced velocity

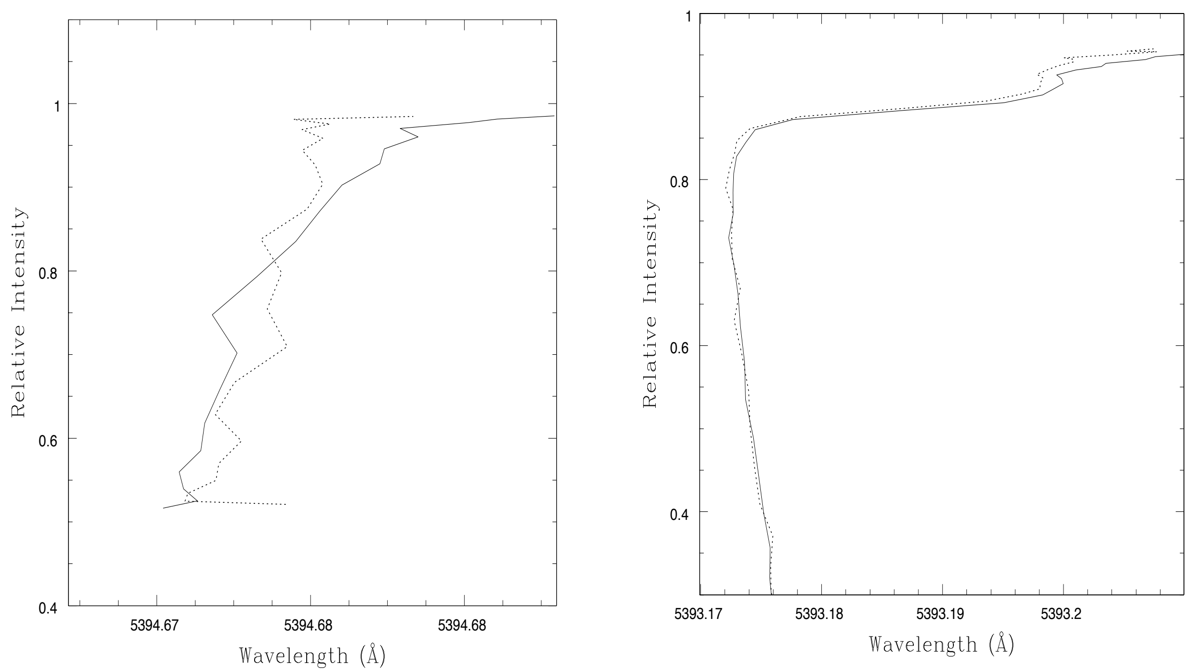

Figure .2: The line bisectors corresponding to the photospheric lines in Figure 1. (*Left*) Bisectors for the Mn I line. The solid line is the bisector from the 2009 spectrum obtained during the extended minimum of Cycle 23 while the dashed line is the bisector acquired in 2014 during the current Cycle 24 rise to maximum. (*Right*) Similarly but for the Fe I feature. Note the relative complexity of the bisector for the Mn I line and its apparent variation from solar minimum to solar maximum. By contrast, the Fe I line exhibits comparatively little change

span of the C-shape to magneticeffects on the velocity field in the line formation region. By contrast, the Fe I bisector is more smooth and exhibits little variation from solar minimum to the current maximum.

Given the complexity of the Mn I bisector, we adopted the approach of Povich et al. (2001) in deducing the velocity span by calculating an average velocity displacement from line center utilizing three evaluation points at relative intensities (0.60, 0.75, 0.90). By adopting the average of three evaluation points, the uncertainties in individual velocity spans are minimized. This method yielded a time series of bisector amplitudes derived from 1,704 near-daily spectra obtained from 2007 January – 2014 May. The Lomb-Scargle periodogram of the time series of velocity spans did not yield any significant peaks at solar rotation periods. Thus, variations in the bisector amplitude are not dominated by major active regioncomplexes that could be expected to exhibit a rotational modulation signal, analogous to that seen in the Ca II K line. Therefore, the line bisector amplitude must be affected by a longer-period variation in the background global solar magnetic field (in the region of line formation). The implicit assumption in this supposition is that variability in the line bisector is due primarily to magnetic field-induced effects and not purely hydrodynamical effects.

3. Two-component Magnetic Model of Line Profile Variations

The variation in the core relative intensity is likely a manifestation of the interplay between enhanced heating and Zeeman sensitivity arising from the increase in the globally averaged magnetic flux with the solar-stellar cycle. This effect can be reproduced by simple single-component thermal models. We present an additional perspective that recognizes that enhanced heating occurs in the presence of magnetic fields combined with a consideration of the magnetic sensitivity of, in this case, the Mn I 539.467 nm line, which is characterized by an effective Landé g-factor of 1.857 (indicative of moderate magnetic sensitivity). Following Giampapa et al. (1983), we adopt a two-component model where the observed stellar profile is a combination of profiles from quiet (nonmagnetic) and active (magnetic) regions weighted by the filling factor of active regions, or

$$M(\lambda) \;=\; (1-f)Q(\lambda) \;+\; Af[Z(\lambda \;-\; \Delta_H\;) \;+\; Z(\lambda \;+\; \Delta_H\;)] \;+\; BfZ(\lambda)\;,$$

where M is the observed profile, Q is the reference quiet profile, Z is the unsplit profile, and A and B are constants that depend on the line-of-sight to the field lines. In this approach we have approximated the hyperfinesplitting in the Mn I line with a simple Zeeman triplet representation. The Zeeman splitting is given by $\Delta_H \;=\; 4.7 \times 10^{-13}\; gH\lambda^2$ in units of Å, where H is the magnetic field in Gauss and g is the effective Landé g-factor. Upon Fourier transforming with k as the transform variable and averaging over all possible line-of-sight angles we obtain

$$g(k) \;=\; (1-f) \;+\; \tfrac{1}{4}\tfrac{M}{Q}f[1 \;+\; 3\,\cos(\Delta_H k)]\;.$$

Multiplying the transform of the solar-minimum Mn I profile by the function $g(k)$ and inverse transforming yields the dashed profile in the right panel of Fig. 3, where we adopted a filling factor $f = 0.3$ and a field strength of $H = 500$ G. The similarity of the resulting profile derived from the application of the above model to the quiescent profile is consistent, at least qualitatively, with the results of Vitas et al. (2009). In particular, these investigators claim on the basis of extensive modeling that the sensitivity of the Mn I 539.47 nm line to activity is due entirely to its hyperfine structure. The nearby Fe I 539.317 nm line with an effective Landé g-factor of 1.5 also is sensitive to magnetic fields. The above model could be equally applied to this feature to account for the slight change in core depth noted in Fig. 1. However, the marked difference in the line bisector shapes between the Mn I and the Fe I 539.317 nm lines (Fig. 2) would seem to reinforce the conclusion by Vitas et al. (2009) that it is the hyperfine structure of the Mn I line in the presence of magnetic fields that is the dominant factor in the determination of changes in the line profile shape in the spatially integrated spectrum of the Sun as a star. Our simplified approach is illustrative of the additional perspectives that can be obtained on the variation of magnetically sensitive lines with atmospheric heating and the associated magnetic field regions.

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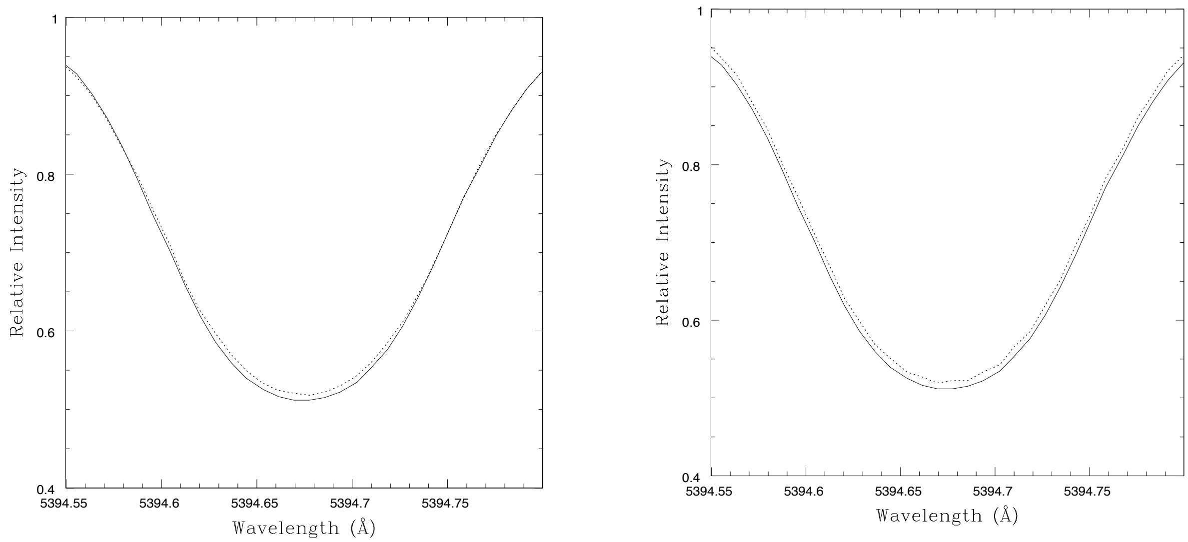

Figure .3: (*Left*) The observed Mn I line profiles recorded during the Cycle 23 minimum (solid) and the current Cycle 24 rise to maximum (dashed). The slight filling in of the line core with increasing globally averaged chromospheric activity is evident in these high signal-to-noise spectra. (*Right*) The same Mn I profile from solar minimum (solid) along with the line profile resulting from the application of a simple two-component model (*dashed*) as described below

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