Quiet-Sun Magnetism Seen with a Mn Line: Km-Sized Magnetic Structures

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Abstract. We observed Manganese lines with large hyperfine structure and used them to disentangle strength from flux in the measurement of photospheric magnetic fields. In observations of the quiet sun with both ASP and THEMIS, we measure flux from the amplitude of Stokes $V$ in Fe lines, and the Mn line, crudely analyzed, places the field strength either above or below a threshold of 600 G, which is set by the atomic structure. In the case of THEMIS observations, having determined magnetic flux and field strength for every pixel, one can estimate filling factors of the magnetic field and determine characteristic scales. Structures at scales smaller than 50 km are revealed.

1. Hyperfine Structure and Quiet-Sun Magnetism

The use of Mn lines for the diagnostics of magnetic fields was prompted by López Ariste, Tomczyk, & Casini (2002) from numerical simulations of polarized line formation in the presence of the Zeeman effect with hyperfine structure (HFS). The predicted profiles were observed later by López Ariste, Tomczyk, & Casini (2003), thus confirming the accuracy of the atomic computations, and opening the path towards its use as a diagnostic tool. Here we report on the use of these lines for the diagnostics of the magnetism of the quiet sun.

“Quiet Sun” is defined as the photospheric regions away from sunspots, plages, and their surroundings (active regions). In the quiet sun, we find the photospheric network, where the advection flows responsible for the supergranulation concentrate magnetic flux in the order of several hundred Mx cm$^{-2}$ at the supergranular boundaries. Inside that network, the internetwork (or intranetwork, as it is sometimes referred to in the literature) seldomly shows magnetic fluxes higher than 10 Mx cm$^{-2}$. A long debate is still ongoing about the nature of those magnetic fluxes. Some observations, using the customary Fe doublet at 630 nm appear to point towards an overabundance of kG fields concentrated in small flux tubes (Domínguez Cerdeña, Sánchez Almeida, & Kneer 2003). This overabun-

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Simultaneous Stokes-V profiles of the Fe doublet (right) and the Mn line (left; the Mn line is the rightmost one in the plot, the two others being Fe lines) for two points in the quiet sun near disk center. Wavelength is in pixels ($\approx 20$ mÅ/px) with red towards the left. The Stokes-V amplitude is normalized to the local continuum.

Image 1. Simultaneous Stokes-V profiles of the Fe doublet (right) and the Mn line (left; the Mn line is the rightmost one in the plot, the two others being Fe lines) for two points in the quiet sun near disk center. Wavelength is in pixels ($\approx 20$ mÅ/px) with red towards the left. The Stokes-V amplitude is normalized to the local continuum.

dance is discussed by other authors using the same lines in the internetwork, and, more importantly, by groups relying on infrared lines for the diagnostics (Lin & Rimmlele 1999; Khomenko et al. 2003). In this latter diagnostics, the few kG files found correspond to the exponential decay of a turbulent distribution of fields, while 400–600 G strong fields are dominant.

Many explanations, of increasing sophistication, have been proposed, including the possibility that the observed lines may not carry information on the field strength (see Martínez González, Collados, & Ruiz Cobo 2006; also Collados, this conference) Use of other lines to increase the amount of information on these regions appears to be essential. For this reason we decided to observe the Mn lines in the quiet sun, in the attempt to disentangle field strength from magnetic flux, which is something that appears to be beyond the capabilities of the Fe lines.

Although the first observations among the ones reported here were made with the Advanced Stokes Polarimeter (ASP; Elmore et al. 1992), it is illustrative to consider first observations made with THEMIS in June 2005. With THEMIS we could observe simultaneously the most interesting Mn lines together with the traditional Fe doublet at 630 nm. Figure 1 shows two selected points (top and bottom) in the quiet sun, in both the Mn and Fe doublet spectral regions. The observations are strictly simultaneous (common shutter for the cameras), and
co-spatial to the extent allowed after correction of the small effect of differential atmospheric refraction (that we estimated to be less than the pixel size of 0′′.2, with a seeing which rarely was better than 1′′). The Fe doublet suggests a magnetic flux roughly 3 times larger for the first point with respect to the second point (approximately 1% and 0.3% amplitudes; cf. right panels of Fig. 1), but in both cases the amplitudes of the two lines are very similar. This is traditionally interpreted as the signature of kG fields that have saturated the stronger line. The simultaneous observation of the Mn line, however, gives a different picture. For the first point (top), the strong flux is accompanied by a “normal” Stokes $V$ of the Mn line. This indicates that the Mn atom is in the Paschen-Back regime for the HFS, which, for this line, takes place above 800 G. One can therefore conclude with confidence on the actual presence of kG fields in this strong flux region. For the second point (bottom), Stokes $V$ of the Mn line shows instead a characteristic spectral signature (pixel #140) due to the HFS, which can only appear below 600 G for this particular line. We must then conclude that, despite the similar Stokes-$V$ amplitudes of the two Fe lines, the magnetic field in the second point is dominated by strengths of the order of several hG ($1 \text{ hG} = 10^2 \text{ G}$). This analysis of the observations of Fig. 1 is rather crude, but clearly illustrates the diagnostic potential of the Mn lines.

It is important to stress the physical origin of these peculiar spectral features observed in the Mn lines, which may at a first glance be dismissed as polarimetric
Figure 3. Ratio of amplitudes of the main Zeeman lobe of Stokes $V$ and the spectral feature due to hyperfine structure, as a function of field strength. The Mn line at 5539 Å was computed in a Milne-Eddington atmosphere to get representative profiles.

noise. Figure 2 shows a full-slit image of the spectral domain of the Mn line with increased contrast. The spectral feature that we recognize as being due to the HFS can be seen as a continuous, coherent feature along the slit. In the strong-flux points (e.g., pixel #55 or #72), the Mn line appears similar to the neighbouring Fe lines. But in pixel #90 through #100, the Mn line has a different shape, which stays coherent for about 10 pixels, and despite the noise. Such spatial coherence confirms the physical origin of this spectral feature. In addition, this feature is completely reproduced, in both wavelength position and amplitude, by our modeling of the Mn line.

The spectral feature associated with HFS varies in amplitude as a function of the field strength acting on the Mn atom. Figure 3 shows the amplitude ratio, $r$, between the main lobe of Stokes $V$ (due to the Zeeman effect) and the HFS spectral feature, computed for the Mn line at 5539 Å in a Milne-Eddington atmosphere. This ratio can be directly measured on the profiles, providing us with a proxy of field strength. However, we can go a step further. It is commonly accepted that quiet-sun magnetism is the product of a distribution of different field strengths that mix at spatial scales well below the spatial resolution of present-day observations (Socas-Navarro & Sánchez Almeida 2003). This is also confirmed by magneto-convection simulations (e.g., Cattaneo 1999). Rather than measuring a field strength per pixel, one should therefore determine the PDF of the distribution of fields in every pixel. As a preliminary approach, we can assume that a pixel contains two different field strengths, say 1500 G and 325 G, embedded in a large region with no field. The field strength of 1500 G is traditionally quoted for quiet-sun magnetism (e.g., Stenflo 1973). The value of 325 G was chosen instead to fit the largest amplitude observed in our ASP data of June 2002, and it corresponds to a theoretical amplitude ratio $r = 2.25$. In this oversimplified picture of quiet-sun magnetism, the only unknowns are the
corresponding filling factors, because the field strengths are fixed. It is evident that if we measure the total magnetic flux in the pixel, $F_t$, and the amplitude ratio $r$ between the main Zeeman lobe of Stokes V and the HFS spectral feature (when present), we can determine the two filling factors $\alpha_{kG}$ and $\alpha_{hG}$ for the two assumed field strengths from the equations

$$\alpha_{kG} = \frac{(F_t - 325 \alpha_{hG})}{1500},$$  

$$\alpha_{hG} = \frac{2.25 \cdot F_t}{r \cdot 325}. $$

Obviously these equations can be rewritten for any pair of field strengths that are considered more adequate. However, the crudeness of the model will only provide order-of-magnitude values for the filling factors, so there is no point in refining the field strengths adopted here.

We applied Eqs. (1) and (2) to ASP observations made in June 2002. Unfortunately we did not have enough photons to reach the required S/N ratio per pixel, so we had to average over large portions of the scan to increase the S/N ratio and get measurable Stokes-V profiles for the Mn line. Thus we do not have single-pixel results but rather 10 points corresponding to different regions selected for the averaging. We could distinguish the network from the internetwork regions by placing a cutoff at $10^{-3}$ in the amplitude of Stokes V of the stronger Fe line present in the observed spectral domain. Figure 4 plots the filling factors for network (left) and internetwork (right) as a function of the total magnetic flux.

For strong fluxes above 200 Mx cm$^{-2}$, our results show that kG and hG fields occupy similar areas of the network ($\sim 20\%$), so that the kG fields are dominant. The scenario changes for fluxes below that threshold. Now hG fields occupy up to 60\% of the area, while kG fields drop to less than 5\%. Whatever the mechanism that makes kG fields appear at a significant level, it requires flux densities larger than 200 Mx cm$^{-2}$. For fluxes below 10 Mx cm$^{-2}$, our results indicate the absence of kG fields in the internetwork, with a filling factor at most of 0.2\%. Most of the magnetic flux is therefore carried by the hG fields (approximately 1\% of the area). It should be stressed that these numbers consider granules and
intergranular lanes altogether, and are therefore just an average of these two different regions inside the internetwork.

In June 2005 we observed the Mn line at 5539 Å simultaneously with the Fe doublet, as well as other interesting Mn lines, also subject to strong hyperfine coupling. This dataset has so far been analyzed only to the extent of estimating the total flux $F_t$ and the ratio $r$, in order to infer one field strength per pixel and the corresponding filling factor. For these observations, we made sure that the S/N ratio was large enough to ensure a meaningful Stokes-V profile of the Mn line for most of the pixels covering the observed quiet-sun region.

Filling factors have historically been introduced to resolve inconsistencies in the results of spectro-polarimetric inversions (e.g., of the Fe doublet) that are run under the assumption of uniformly filled magnetic regions with a single-valued magnetic field. Although they are implemented in inversion algorithms with their proper physical meaning (fraction of the resolution element filled with magnetic field), they are rather inverted as free parameters of the profile fitting procedure. However, the presence of scattered light in the instrument or in the earth atmosphere, or even atmospheric changes along the line-of-sight, can all be possible sources for such inconsistencies, so that the physical meaning of filling factors can be lost in these inversions.

In a magnetic diagnostics based on the Mn lines, instead, the filling factor is properly derived as the quotient of flux and field strength directly from the observations, since both flux and field strength are directly measured on the profiles—the flux from the total amplitude of Stokes $V$, and the strength from the ratio $r$. While one may possibly argue about the errors of two such measurements, it is evident that this diagnostics preserves the correct physical meaning of the filling factor after inversion.

At THEMIS we took a scan of 1″5 along the equator, near disk center. Perpendicularly to the equator we had the full slit length of 31″. This scan covers an area of $21700 \times 1050 \text{km}^2$. Figure 5 shows the scan with circles representing the measured filling factor (we adopted a circular shape only to simplify the plotting procedure). The radius of each circle sets the upper limit on the total size of the magnetic structures inside the corresponding pixel. The network region slightly past mid-slit towards the right have fields that in many cases fill more than 50% of the pixel. Elsewhere in the internetwork, fields are rarer instead. It is noteworthy that we are able to detect magnetic structures on spatial scales of 10–40 km. In a certain sense, through the polarimetry of the Mn line, we are reaching spatial resolutions well beyond the diffraction limit of the telescope. Of course this technique does not allow to determine the spatial distribution of fields inside the pixel, but it allows to assert unambiguously the presence of magnetic structures with such spatial scales inside the pixel.
2. Conclusions

We exploited the signature of hyperfine structure of certain lines of Mn to learn about the magnetism of the quiet sun, as previously suggested by López Ariste et al. (2002). The analysis tools are still very crude, but they have already succeeded in identifying a cutoff flux density of 200 Mx cm$^{-2}$, above which kG fields appear to dominate the magnetized atmosphere. Below this cutoff, kG fields are scarce, with filling factors at least one order of magnitude smaller than the hG fields, for the average internetwork (granules and intergranular lanes taken together). We have also shown how the Mn lines can be used to obtain reliable estimates of the magnetic filling factor, which can then be translated into measurements of magnetically filled areas. Preliminary results indicate the presence of magnetic structures with spatial scales of 10–40 km in the internetwork.

References

Martínez González, M. J., Collados, M., & Ruiz Cobo, B. 2006, these proceedings