Multiline Zeeman signatures as demonstrated through the Pseudo-line

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ABSTRACT

Context. In order to get a significant Zeeman signature in the polarised spectra of a magnetic star, we usually ‘add’ the contributions of numerous spectral lines; the ultimate goal is to recover the spectropolarimetric prints of the magnetic field in these line additions.

Aims. Here we want to clarify the meaning of these techniques of line addition; in particular, we try to interpret the meaning of the ‘pseudo-line’ formed during this process and to find out why and how its Zeeman signature is still meaningful.

Methods. We create a synthetic case of lines addition and apply well tested standard solar methods routinely used in the research on magnetism in our nearest star.

Results. The results are convincing and the Zeeman signatures well detected; Solar methods are found to be quite efficient also for stellar observations.

Conclusions. The Zeeman signatures are unequivocally detected in this multiline approach. We may anticipate the outcome magnetic fields to be reliably detected beyond the weak-field approximation. Linear polarisation in the spectra of solar type stars can be detected when the spectral resolution is sufficiently high.

1. A general introduction to ZDI and PCA

In the 1980s it became clear that cool stars, mainly rapid rotators, exhibit solar type activity. Rapid rotation is one of the essential ingredients to the stellar dynamo. While there is not yet any completely satisfactory theory or model of the solar or the stellar dynamo, it is quite clear what drives such a process, viz. convection, rapid rotation and differential rotation. Tentatives to detect the Zeeman effect in these active stars however failed for 2 main reasons:

- The magnetic configuration of the stellar magnetic fields can be quite complex. The simultaneous appearance of opposite magnetic polarities may lead to cancellation of the respective contributions to the integrated polarisation signal in the stellar spectrum.
- The broadening of the spectral lines due to even moderate stellar rotation rates can become a serious handicap when measuring the magnetic field of the star.

Consideration of these two aspects was at the object of paper 1 (Semel 1989) where the term ZDI stood for the detection of a Zeeman signature thanks to the Doppler effect. The latter can help to disentangle the contributions from opposite magnetic polarities and their respective opposite polarisation which otherwise may cancel. Thus the combination of Zeeman and Doppler effects is one of the reasons why the detection of the Zeeman effect in fast rotating active solar type stars becomes possible. Nowadays however the term ZDI is often understood as magnetic mapping of the stellar surface, based on the inversion of Stokes profiles (frequently only I and V) sampled over a full period of rotation.

We therefore propose the term Multiline Zeeman Signature (henceforth MZS) to denote a method for just the detection of a mean Zeeman signature, using numerous spectral lines. We shall not attribute any direct physical meaning to the MZS. We simply require the application of an operator O (or a detector O) to a polarised spectrum, creating a particular MZSo. The inversion code then should use exactly the same operator O for the comparison and inversion of the observational data in order to get the desired information on the magnetic field. We leave this demonstration to a forthcoming paper.

In this paper we discuss the problem of Zeeman signatures in the polarized spectra of solar type stars. It may concern any of the three components of the magnetic vector, at any stellar point and in any of the four components of the Stokes vector in the spectrum of the particular stellar point. (and the SUN as a special case).

This paper does not treat inversion. This last is postponed to the forthcoming papers. By inversions...
we mean recovering not only magnetic field but also the model of atmosphere!

This paper does not resolve mixtures of polarities. It is left for later steps.

We therefore turn back to the more elementary methods, like spectral line addition, but this time we overcome the limitation of the weak-field approximation. The first successful MZS tentatives consisted in the adding up of the circular polarisation of selected spectral lines. Paper I (Semel 1989) recommended the de-blending of the spectral lines prior to addition, but Semel & Li (1996) showed that simple coherent addition of spectral lines gave satisfactory results. Some 200 spectral lines were added in that work to yield significant detections.

This straightforward method of line addition was later improved by Semel (1995). A list of spectral lines of interest was created. These spectral lines were labelled by wavelength $\lambda_i$, equivalent width $w_i$, and effective Landé factor $g_i$. In the next step, each spectral line was represented by a Dirac function $\delta(\lambda - \lambda_i)$ and transformed, as explained in Semel (1989), to the Doppler coordinate $X_i$, with $dX = c \, d\lambda/\lambda$, and $c$ the velocity of light. The convolution of the observed circular polarisation spectrum $V(X)$ and the line list results in a pseudo line $f(x)$ given by

$$f(x) = \Sigma_i \left( w_i \cdot g_i \right) V(x - X_i) / \Sigma_i \left( w_i \cdot g_i \right)$$

As a rule, the convolution by means of a Fourier transform is found to be quite efficient. Donati et al. (1997) introduced the postulate that in a given observed Stokes spectrum the shape of the Zeeman signature in circular polarisation is identical for all spectral lines. Individual Stokes $V$ profiles are assumed to correspond to the common basic Zeeman signature, multiplied by the effective Landé factor and by the central depth of the line in question. Based on this assumption, a particular MZS (the basic Zeeman signature) is extracted by means of a least squares method from the observed spectrum. In combination with maximum entropy codes (Brown et al. 1991, Donati & Brown 1997), LSD based Stokes $I$ and $V$ profiles have been used for the production of magnetic surface maps of quite a large number of stars with great success.

The methods and techniques used in solar polarimetry and magnetometry have subsequently been applied to the stellar problem. The solar case is always the easier one, because one can often isolate just one point at a time and get strong enough signals for each wavelength pixel observed. Here the Doppler effect due to the solar rotation does not present any problem. On the contrary in the case of a star, the signals from all the points over the visible disc are mixed up. Also, the star being faint, the signals in its spectrum are much weaker and we need to collect the contributions over a significant portion of the spectrum before we get reasonable signal strengths. Moreover, the Doppler effect due to the stellar rotation cannot be neglected.

We therefore start our present discussion with solar conditions, i.e. a magnetic field observed in just one point and we shall take a few spectral lines formed in the presence of a magnetic field and calculate the Stokes vectors at spectral resolutions common in solar physics, some 3 millions. We then add up the Stokes parameters of all the spectral lines and subsequently reduce the spectral resolution to stellar conditions, say 75000, obtaining a kind of pseudo-line. We then examine the invariants that we have already found in solar magnetism, as the displacement of the centre of gravity that yields a good approximation to the longitudinal component of the magnetic field. Our purpose here is to assess to what degree the new pseudo-line still contains all the information on the magnetic field that was present in the individual spectral lines in our sample, well beyond the weak-field approximation. Such will be the first result of this work.

A similar procedure will be followed with the linear polarisation signatures. Linear polarization is often neglected in stellar polarimetry seeking Zeeman signatures in the assumption that it will present amplitudes too small to be observed. The second result presented in this paper, the first of a series, will be the demonstration that, at appropriate spectral resolutions, the linear polarization due to the Zeeman effect produces sensible signatures useful for diagnostics of the stellar magnetic fields.

In the following papers of this series we will apply recent solar inversion procedures to the synthesised Stokes profiles, and we compare the results obtained with the original solar resolution with the pseudo-line smoothed to stellar resolution (paper II, Ramirez Velez et al., 2008, submitted); then we shall replace the Milne-Eddington model atmosphere used in the radiative transfer computations by detailed line formation calculations in an empirical model atmosphere for a variety of magnetic field configurations. Application of principal component analysis (PCA) has been proven very effective in solar magnetometry and, analogously to the solar case, a database will be created and the PCA eigenvectors derived, applying the PCA-ZDI detection to just one magnetic point on the star. In addition we shall discuss how to apply our approach to some few points on the stellar disc well separated by significant Doppler effects (Paper III). Finally in Paper IV we shall have to treat the more realistic case of continuous distributions of fields over the stellar surface. Here, the orthogonality of the eigenvectors is not conserved for adjacent stellar points (that is for small differences in the Doppler shifts). The LSD technique may be proposed for such cases.

2. Invariants in Zeeman analysis.

The effects of a magnetic field on the line profiles are quite specific and essentially comprise polarisation and symmetry properties. Both circular and linear polarisation appear in spectral lines: linear polarisation is symmetrical in wavelength, circular polarisation on the other hand is antisymmetric. These manifestations are very particular to magnetic fields. For instance, only magnetic fields may create circular polarisation in spectral lines. The detection of such polarisation is unambiguous evidence for the presence of magnetic fields. It is our conviction that we can rely on some invariance properties in the spectropolarimetric data. Here we present a few specific arguments.

2.1. The centre of gravity method.

This method applies only to circular polarisation; it is well studied in solar magnetism and described in a number of papers of which at this point we mention only Rees et al. (1979)( and see references therein). In the limiting case of optical thin layers in LTE, the centre of gravity shift of the line profiles observed in circular polarisation is proportional to the longitudinal component of the magnetic field. This
still holds true, even for line formation in optically thick layers, in the limiting case of weak magnetic fields. Usually, this simple method is still a fair approximation in the more general case, but there are a few exceptions – see Semel (1967) for theoretical demonstrations, experimental tests and some exceptions.

2.2. The weak-field approximation.

This approximation was first introduced by Sears, (1913) and was used for observations with solar magnetographs. It was the first assumption in the first paper on ZDI (Semel, 1989), henceforth paper I. Does this approximation also hold for stronger fields? In the following we shall present some relevant calculations concerning its application in the context of stellar magnetic field measurements.

Let us now analyse the weak-field approximation within the framework of the centre of gravity method. Consider the situation where the Stokes $V$ parameter is fully antisymmetric and $I$ is symmetric (in the absence of velocity gradients). When the weak field approximation holds, $V$ is nearly proportional to the first derivative of $I$, but this is no longer true for larger Zeeman shifts. However, if the spectrum is smoothed, the weak field situation is recovered to some extent and the weak-field approximation can be extrapolated to stronger fields. Indeed, smoothing neither affects the centre of gravity shifts nor the symmetry characteristics of $I$ or $V$, while the Zeeman shifts become small relative to the widths of the smoothed spectral lines. This will be shown explicitly below with a numerical demonstration. The weak-field approximation used in paper I can thus still hold in stellar spectropolarimetry thanks to the low spectral resolution.

2.3. Strong field - all Zeeman components separated.

This is a simple case where magnetic measurements are possible with no reference to a model atmosphere since the polarisation states of all the components are completely determined by the orientation of the magnetic field. When the state of polarisation of any of the $\sigma$ components is known it is possible to determine the orientation of the field except for the ambiguity in the azimuth. The separation of the components determines the strength of the field.

2.4. Inversion of full Stokes polarimetry.

Even the use of a simple M-E model can give reliable results provided that the parameters of the model are not fixed but determined in the inversion procedure. Models more sophisticated than M-E could determine even gradients! All these approaches are improved by multiline techniques.

2.5. Our program

We first present very simple examples but at the end, using our approach with the PCA technique, ZDI will be pushed to its limits. To start with, we stick to the original meaning of ZDI in its limited sense, i.e. magnetic fields occur only at “isolated” points on the stellar surface. Only much later will we tackle ZDI in the common and broader sense as the mapping of stellar surfaces.

3. Multiline Zeeman Signatures in circular polarisation (MZSV) applied to the spectral lines of a single multiplet of neutral iron.

For this demonstration we selected the spectral lines of one specific multiplet of neutral iron (816) and we used a simple Milne-Eddington (M-E) model, characterized by a linear with optical depth source function, keeping all other parameters constant with depth. The only other free parameters of the model will be the Doppler width, line damping, and opacity ratio of the line core respect to the continuum on the thermodynamical side of the line formation, a magnetic field vector and a line-of-sight velocity field.

The lines of multiplet 816 of Fe I have often been used in solar magnetic field measurements. We keep in the present work a high spectral resolution of 100 m/s, i.e. a resolution of 3 millions, and then study the effect of smoothing, bringing the resolution down to 75000, which corresponds to sampling with a step of about 4 km/sec. Without loss of generality we employed a M-E model, using the code Diagonal as described in López Ariste and Semel (1999) with only one layer. This code can be extended to a large number of layers and fit any LTE model. The atomic parameters are listed in Table 1. For the M-E model we took $\beta = 10$ and $\eta$ equal to twice the relative strength of the components of the multiplet as given by Allen (1991). Doppler broadening is 21 mA as in sunspots, and damping is taken to be 0.01.

3.1. A justification of the M-E model, blending, and Li Jing’s method

Using the M-E model facilitates the analysis and does not require heavy calculations. Calculating each line separately with a M-E model may appear subject to doubt, but the experience of solar magnetism has shown that when the parameters are not fixed but fitted to the observations, the M-E model is quite good. Selecting multiplet 816 of Fe I ensures the validity of LS coupling and the easy determination of Zeeman patterns, relative line strengths etc.

Line blending seemed to be a serious matter in paper I (Semel, 1989). However, Semel and Li (1996) have shown that when numerous lines are “added” coherently, the blending lines are added incoherently and therefore only contribute to the noise (which in turn is reduced when the number of spectral lines increases). In Figs. 1-5 we will show each profile in detail and one can see the limitation of the weak field approximation. Now, when we add the lines and

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1 These steps are necessary for a better understanding
2 to be explained later
3 Saturation has always been an important issue in solar and stellar magnetic field measurements. Here it is included in the procedure and we have to use the same procedure when we get to the inversion.
Table 1. The list of spectral lines of multiplet 816 of neutral iron. The relative strengths correspond to LS coupling as given by Allen, 1991, p. 62. The ratio $\eta$ of line to continuum absorption is obtained from the relative strengths multiplied by a factor of 2; the latter is chosen arbitrarily.

| No. | $\lambda$ (Å) | upper level | lower level | relative strength | $\eta$ |
|-----|----------------|-------------|-------------|-------------------|-------|
| 1   | 6400.010       | $^5D_3$     | $^5P_1$     | 27                | 54    |
| 2   | 6411.658       | $^5D_3$     | $^5P_2$     | 14                | 28    |
| 3   | 6408.031       | $^5D_2$     | $^5P_3$     | 5.25              | 10.5  |
| 4   | 6246.334       | $^5D_4$     | $^5P_3$     | 7                 | 14    |
| 5   | 6301.515       | $^5D_3$     | $^5P_2$     | 8.75              | 17.5  |
| 6   | 6336.835       | $^5D_1$     | $^5P_1$     | 6.75              | 13.5  |
| 7   | 6141.734       | $^5D_2$     | $^5P_3$     | 1                 | 2     |
| 8   | 6232.661       | $^5D_1$     | $^5P_2$     | 2.25              | 4.5   |
| 9   | 6302.507       | $^5D_0$     | $^5P_1$     | 3                 | 6     |

then reduce the resolution we recover the weak-field approximation (Fig. 6-10).

A comment on blending: each spectral line may appear several times, once in the coherent addition, and then each time when the line is “blending” in the field of another nearby line. However, in the latter case it appears in a non-coherent way and always in another position (in wavelength). When the line is blending, its contribution is “arbitrarily” situated and has only a little effect.

3.2. Discussion of the figures

With very high spectral resolution, (see Figs. 1-3), the circular polarisation changes shape and details clearly depend on the field strength. For instance, the anomalous dispersions appear for fields stronger than 1 kG as reflected in the reversal of Stokes $V$ at the line centres. This has no counterpart in the weak-field approximation.

Fig. 1. The 9 lines, (line 1 to 9 from left to right) of multiplet 816 of neutral iron – see Table 1 – put together with a spectral resolution of 3 millions and sampling of 100 m/sec, corresponding to steps of about 2.1 mÅ m. Magnetic field with $B = 500$ G and inclination $50^\circ$. The upper curves (continuous) show $I$ and the lower curves (dashed) $V$.

Fig. 2. The same as Fig. 1 but with a field of 1500 G.

Fig. 3. The same as Fig. 1 but with a field of 2500 G.

Fig. 4. The case of 500 Gauss. The pseudo-line resulting from the addition of the nine lines (thin continuous line), then smoothed by factor 40 to reduce the spectral resolution to 75000 (thick continuous). Bottom: The circular polarisation added (dashed) and smoothed (thick dashed). The derivative of the smoothed intensity (points).
Fig. 5. The same as Fig. 4, but for 1500 Gauss.

While we know from the solar physics that the centre of gravity method really indicates the longitudinal component of the magnetic field, the application of the weak field approximation seems of doubtful validity when we examine the individual line profiles in Figs. 1-3. However, the centre of gravity is a linear operator and commutes with the algebra of line addition and with smoothing. So we may proceed to operate on the pseudo-lines “observed” in circular polarisation as shown in Figs. 4-6. In these figures, the curves for the Stokes profiles become smoother and one can imagine that we eventually recover the essential features of the weak field approximation! We anticipate that with our approach we may recover, in a stellar object, at least any astrophysical result that may be found through the weak-field approximation. More sophisticated methods of inversion will be described in the following papers.

3.3. Critical discussion of the C.G. method, unresolved magnetic fields and Fig. 7

Even the best solar telescope can not resolve the magnetic element in a solar faculae. One way to tackle the problem was to turn to a kind of the filling factor algebra. An account is given in (Semel, 1981). With the help of the C.G. method one could calculate the relative magnetic curve of growth.

However, it is beyond the scope of this paper. In short, Fig. 7 is symbolic and not a solution of the problem. The C.G. may be a good tool to start, but the real work must be followed by an inversion code. (Landstreet, 2008) warns us that the errors in magnetic field determination by use of Fig. 7 reach several hundreds gauss. While the C.G. method was useful at early time, for the determination of solar magnetic fields, it is not recommended today. In Fig. 7, we wanted to show that the pseudoline contains a Zeeman signatures of the LOS component within 95 percents of certainty. The appropriate inversion will be the object of the next paper. For further discussion of the C.G. method applied to stars see (Stift M., 1986) and (Leone F. & Catanzaro 2004)

3.4. Conclusions for the first part: Zeeman circular polarisation

The pseudo-lines are not simple spectral lines in the sense that they have no wavelength and are not characterised by specific atomic parameters such as the excitation potential. Moreover, in the more general case they do not correspond to a particular chemical element, and no specific spectroscopic term is attached to them. Still they contain a lot of information on the astronomical objects we are interested in. What is important: the Zeeman signatures do not disappear in the pseudo-lines! Giving up the weak field approximation, we may look for more sophisticated methods of determining magnetic fields. Applying for example PCA procedures, we can obtain more parameters than with methods limited by the weak field approximation.
4. Spectral resolution and the observation of linear Zeeman polarisation in solar type stars

Carroll et al. (2007) state that as a rule of the thumb, the Zeeman linear polarisation is at least one order of magnitude lower than the circular one. Now, if our line of sight (henceforth LOS) is not a preferred direction for the stellar magnetic field and therefore its three components (the longitudinal one and the two perpendicular to the LOS) have all equal probabilities, than on the average, the transverse component is $\sqrt{2}$ times stronger than the LOS component. The average of the angle between the magnetic vector and the LOS should thus be $\approx \arccos(1/\sqrt{3}) \approx 54^\circ$. From solar physics we know that kG fields are not only found in sunspots. But can we assume that Kilogauss fields are common also in solar type stars? If yes, why does the linear polarisation escape observation? In the following, we try to answer this question and we also suggest a remedy.

4.1. The most probable angle between the LOS and the local magnetic vector.

Let us call this angle $\psi$ and take it between $0^\circ$ and $90^\circ$, say positive LOS component. The average $\bar{\psi}$ is 1 radian if all directions have the same probability; the median angle is $\psi_{\text{Median}} = 60^\circ$. In other words, there are as many orientations between $0^\circ$ and $60^\circ$ as between $60^\circ$ and $90^\circ$. For the case of negative LOS longitudinal fields, $90^\circ < \psi < 180^\circ$, the results for $\bar{\psi}$ and for $\psi_{\text{Median}}$ are deduced similarly. In conclusion, $\psi$ is likely to be nearly $60^\circ$. In the following we define the Stokes parameter $Q$ as perpendicular to the magnetic field. We will show now that $Q$ is likely to be significant. In the next figures we see that for 1 kG and $\psi = 60^\circ$, MZSQ $\approx 0.7$ MZSV for high spectral resolutions. Now $Q$ changes with $\lambda$ twice faster than $V$, so that for current high spectral resolutions, say 60000, $Q$ shrinks much more than $V$. Moreover, $Q$ changes sign when the azimuth changes by $90^\circ$, while $V$ changes sign when $\psi$ changes by $180^\circ$. Both effects may be reduced by increasing spectral resolutions, say 120000. As is seen in Fig. 8, $Q$ is preserved considerably and spatial resolution of the stellar surface is improved as well; this is shown in Figs. 12-17.

4.2. Conclusions for the second part: Zeeman linear polarisation

We have used the pseudo-line technique to show how to extract a Zeeman signature for linear polarisation in a way similar to what we did in the first part for circular polarisation. The first conclusion concerns the spectral resolution required. With a resolution superior to 100000, we can probably detect significant signals in linear polarisation in the spectra of solar type stars! Such a resolution has been achieved in spectroscopic tests with UCLES at the AAT with the 79G/mm grating (see, for instance, Lopez et al. 1999). A single observation of linear polarisation in the spectrum of a solar type star has been performed in 2004 (see Semel et al., 2006). The linear signal observed was indeed four time less than the circular one, but still significant. There is definitely an interest to proceed in this direction.

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Fig. 10. I,Q,V. The same field as before, original resolution 3 millions (thin). Resolution 60000 (thick); Note that Q is reduced considerably for 1000 Gauss with the low resolution.

Fig. 11. I,Q,V. $H = 3000$ Gauss. Original resolution (Thin).

Fig. 12. AS in the last figure but with resolution 120000 (thick)

Fig. 13. AS in the last figure but with resolution 60000 (thick) Note that for field as high as 3000 Gauss, Q is still detectable even with 60000 resolution

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