Hyperfine Structure as a Diagnostic Tool of Solar Magnetic Fields

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Abstract. We present the use of hyperfine structure as a diagnostic tool for photospheric magnetic fields. Many lines in the solar spectrum show evident signature of hyperfine structure in the form of broadening, asymmetries and/or subcomponents. These signatures become even more remarkable when seen in polarization. Among the many atomic species showing these effects, we have selected Mn as the most interesting from the point of view of the amplitude of those signatures. We have performed radiative transfer of several Mn 1 lines including hyperfine structure under Milne–Eddington model atmospheres. The results show anomalous Stokes profiles for “weak” fields that evolve into normal profiles as we increase the field strength and approach the Paschen–Back regime of the line. Interestingly, the presence of the anomalous features in the profiles is only dependent on the intrinsic intensity of the magnetic field, and not on its apparent flux. We therefore propose the use of these lines as a very straightforward diagnostic for the real distribution of fields in the photosphere.

1. Introduction

The hyperfine structure has been long neglected in the study of the solar magnetic fields. Sometimes for the reason that it was unnecessary to undergo the complication of computing spectral lines with hyperfine structure when other lines where sensitive enough to the magnetic field and easier to handle. Furthermore, the most commonly observed lines in the solar spectrum like those of Fe or Ca do not have hyperfine structure.

It has also been argued that hyperfine structure is too small a perturbation to be seen in the thermally broadened profiles of the solar atmosphere. Kurucz (1993) strongly argues against this idea and points to several examples in the solar atlas for which the signature of the hyperfine structure in the profile is clear. In Fig. 1. we show examples of two Mn lines at 5537 and 8740 Å for which the presence of hyperfine structure is evident in terms of profile asymmetries and subcomponents.

López Ariste et al (2002) argued from a theoretical standpoint that the computation of the polarization of lines with hyperfine structure was worth the effort as these lines showed particular features which depended only on the strength of the magnetic field. Lines without hyperfine structure (like the commonly used KeI lines at 630nm) can be very sensitive to the magnetic field but their
polarization mostly depends on the magnetic flux across the resolution element. It is therefore very difficult to disentangle, for example, cases in which we find strong and concentrated fields from cases with weak and ubiquitous fields, both cases resulting in the same magnetic flux. Inversion codes are required to take advantage of the very tiny differences in the functional dependence on the magnetic flux between the different Stokes parameters that can help disentangle field strength from flux. But the presence in lines with hyperfine structure of features that are present for given ranges of magnetic field strength (while the amplitude of those features is still a function on the flux) constitutes a strikingly clear diagnostic tool that can easily tell apart cases with the same magnetic flux but different distribution of field strengths.

![Graphs showing spectral lines](image)

Figure 1. Examples from the solar atlas of two spectral lines from Mn I with a clear signature of the underlying hyperfine structure. At right the Mn I line at 87401 Å shows multicomponents. At right the Mn I line at 5537.8 Å is broad and asymmetric.

In this work, after reviewing the results of López Ariste et al (2002) we present the first observations of several lines of Mn I where the hyperfine signature is very clear and follows the theoretical predictions of that work.

2. Radiative transfer in lines with hyperfine structure

Hyperfine structure is due to the coupling of a non-zero angular momentum of the nucleus of the atom with the usual orbital angular momentum of the electron. The magnitude of this coupling is proportional to the electric dipole and magnetic quadrupole of the nucleus as well as to actual value of the nucleus angular momentum. In order to compute its effect on the observed Stokes profiles one needs to solve the energy perturbation due to the hyperfine structure into the orbitals of the studied atom. This perturbation adds up to the one caused by the external magnetic field through the Zeeman effect and in general one cannot say that one is bigger than the other. Therefore both perturbations should be solved simultaneously by computing the Hamiltonian of the addition of both and solving for its eigenvalues and eigenprofiles, usually with numerical algorithms. A contribution due to the spin of the nucleus itself is usually neglected.

In Fig.2. we see an example of the splitting under the effect of an external magnetic field of an atomic level with hyperfine structure. We can identify three regimes in the magnetic sublevels separation. For weak fields the magnetic field...
acts on the total angular momentum \( F = I + J \) and we see a linear separation of the magnetic sublevels characterized by the projection \( M_F \). As the magnetic field increases, the linear splitting is lost and one can observe interactions between the different sublevels corresponding to different values of \( F \). In fact \( F \) stops being a good quantum number. For higher magnetic field a full restructuration of the magnetic sublevels has occurred and we recover the symmetries of the angular momentum \( J \) to which the hyperfine structure is just a negligible perturbation. We have entered into the Paschen-Back regime for the hyperfine structure.

![Graph showing energy splitting vs magnetic field](image)

**Figure 2.** Example of splitting in energy of the magnetic components of the hyperfine sublevels \( F = 1, 2, 3 \) and 4 (from top to bottom) of the MnI level \( \gamma^6P_{3/2}^0 \) in the presence of an external magnetic field of growing strength. Note the three different regimes in the organization of the components for weak, intermediate and strong (or Paschen-Back) regimes as described in the text.

López Ariste et al (2002) computed the polarized radiative transfer of lines from the Mn atomic species in the presence of magnetic field for the full case, from weak fields up to the Paschen-Back regime. Manganese was selected among other atomic species with hyperfine structure present in the solar spectrum because of the clear signature of the hyperfine structure in the spectral lines as seen in the solar atlas. The coupling between the nuclear angular momentum \( I \) and the electrons total angular momentum \( J \) in Mn is particularly strong and the transitions between different levels are such as to increase the effect of this coupling on the visible profiles. Fig.1. gives two particular examples of Mn lines in which the features due to hyperfine structure are remarkable in terms
of asymmetries and subcomponents. A Milne-Eddington atmosphere model was selected for these calculations as a simple model, still able to reproduce many photospheric lines to an acceptable level. The non-magnetic parameters of the Milne-Eddington model were obtained from a rough fit of every particular line to the profile in the solar atlas (Kurucz et al.1984). All the cases with different magnetic field conditions share the same thermodynamic parameters. While this is not an acceptable situation, it should be enough to illustrate the possible Stokes profiles to be expected from observations or from more realistic cases.

The Stokes profiles obtained in these calculations follow the separation into three regimes we found in Fig. 2. Fig. 3 shows three examples of the Stokes $Q$ and $V$ profiles for magnetic field strengths corresponding to the weak field (100G), intermediate (600G) and Paschen-Back (900 G) regimes of the atomic levels involved in the spectral line at 5537 Å of MnI. We call the attention of the reader to the fact that the actual field strength for which a given line is in a particular regime depends on the atomic structure of the atomic levels of that transition. Therefore different lines are in different regimes for the same magnetic field strength. After that comment, we see in Fig.3 that in the Paschen-Back regime (at 900 G) the Stokes profiles look like the ones one would expect if no hyperfine structure would have been considered in the calculations. In those conditions we know that the amplitude of the Stokes $V$ profile is proportional to the longitudinal flux. But as we consider weaker fields and we enter into the intermediate regime we notice that new features appear in both the Stokes $Q$ and $V$ profiles, in on case in the form of a multi-peak appearance and in the other one in the form of a core reversal. We realize that while the amplitude of the full profile is still a function of the flux, the presence or non-presence of these new features in the profiles depends exclusively on the field strength. Weaker fields just increase the importance of the new features on the full profile.

In the absence of hyperfine structure, the only way to disentangle flux and field strength goes by the use of sophisticated inversion codes which exploit tiny differences in the way different Stokes parameters depend on the flux. The task is far from easy and the results are not ever conclusive. The use of spectral lines with hyperfine structure provides us with a clear diagnostic of both flux and field strength. By means of these new features we can easily distinguish between cases of high concentrated fields and weak and diffuse fields.

3. Examples of observed Mn lines

In June 2002 we observed several of the Mn lines pointed out in López Ariste et al (2002) with the Advanced Stokes Polarimeter (Elmore et al.1992) on the Dunn Solar Tower at Sacramento Peak. In this section we show some examples extracted from those observations that show that basically the features predicted in the theoretical calculations are present in the solar observations.

In Fig.3, we show images of the 4 Stokes parameters in an exposure across a sunspot for the spectral region around the MnI 5537 Å line. The MnI line is the broad line on the left of the spectrum, while the two other lines present are FeI lines with no hyperfine structure. We notice that the FeI line on the right side has similar amplitudes to the MnI line in all four Stokes parameters and is therefore an adequate benchmark. In Stokes $Q$ (upper right image) we notice
Figure 3. Examples of Stokes $V$ (left) and $Q$ right of the MnI line at 5537.8 Å computed for three different field strengths: 100, 600 and 900G. Note the presence of anomalous extra peaks in the profiles that tend to disappear as we approach the Paschen-Back regime at strong fields. Their presence is a function of the field strength while their amplitude is dependent as usual on the magnetic flux.

how the MnI line shows a multi-peak aspect before entering the penumbra and then midway through it it changes into a normal Stokes $Q$ profile identical in form and amplitude to the FeI line on the far right. In the outer penumbra we should expect a magnetic field strength of less than 1000G, for which this particular line is still in the intermediate regime. As we travel through the penumbra towards the umbra we can expect the field strength to increase and the Mn line to change regime into the Paschen-Back regime. In the Paschen-Back regime the atomic sublevels have reorganized and the line has forgotten the presence of hyperfine structure, showing, as we see, a normal Stokes $Q$ profile comparable to the ones of the Fe lines next to it. A similar transition happens in the Stokes $V$ image. We can appreciate it better in the MnI line at 5470 Å, whose sensitivity to magnetic field strength changes is bigger than the MnI line at 5537 Å shown in Fig3.

In Fig. 3, we show an example of an exposure across the outer boundary of a penumbra in the spectral region around MnI line at 5470 Å, as well as a particular set of Stokes profiles extracted around position #120 along the slit. Here we see clearly that not only Stokes $Q$ and $U$ but also Stokes $V$ (bottom right image) shows an unusual profile in the upper penumbra, while it is normal in the bottom penumbra. The profiles from the upper penumbra that we show at right confirm the presence in Stokes $V$ of a well developed core-inversion feature similar to the ones computed by (López Ariste et al.2002) for the case of the weak field regime. In figure 3, we see another example of this line, this time across a well defined penumbra and for which the Stokes $Q$ profiles still show
Figure 4. Observation of the spectral region around the MnI line at 5537 Å (the broad line on the left part of the region) with the Advanced Stokes Polarimeter across a sunspot. From left to right and top to bottom: Stokes $I, Q, U$ and $V$. Note the transition in $Q$ from the intermediate to the Paschen-Back regime as the magnetic field strength increases towards the umbra of the sunspot. The two other FeI lines present do not have hyperfine structure and do not show the transition.
Figure 5. Observational example of the weak field regime in the Mn I line at 5470 Å. Note the multiple components in both Stokes Q and V. In the bottom a particular profile extracted from the above image.
residuals of hyperfine structure but not so the Stokes $V$ profile (at most one can point to the linear, zero-crossing, part of the profile which is not as linear as it should be). This corresponds well to the intermediate regime in which we see that the Stokes $V$ features are the first to disappear, leaving a normal profile, while the Stokes $Q$ and $U$ profiles are more resilient.

4. Conclusion

We have shown observational examples of the Stokes parameters of lines of MnI with hyperfine structure. We see that these lines show the particular features predicted by the theory as a result of the presence of the hyperfine structure in the atomic levels. Recalling the results of López Ariste et al (2002) we know that while the amplitude of the observed profiles is still a function of the magnetic flux, as in the case of the Stokes profiles of lines without hyperfine structure, the presence or non-presence of those particular new features is only dependent on the field strength. We have shown observational examples in which the presence of these features or its absence have allowed us to place the line in one of the three regimes identified (weak field, intermediate and Paschen-Back) and therefore give crude estimates of the magnetic field strength in which those lines were formed independently of the magnetic flux that we can still determine from the amplitude of the profiles.

The observational examples confirm the main conclusion of López Ariste et al (2002) regarding the interest in the observation of these lines as a clear and useful diagnostic of the general distribution of photospheric magnetic fields.

We have intentionally skipped in this work any attempt of physical interpretation of the crude estimates of magnetic field strengths in penumbra. Only an inversion code adapted to lines with hyperfine structure will be able to provide us with quantitative estimates that can be used in a safe manner for further studies. Because of the particularities of these lines with hyperfine structure we can expect any inversion technique to perform far more efficiently on these lines than in any other line.

Discussion

K.S. Balasubramaniam: Do you include magneto-optic effects in the hyperfine structure calculations?
A. López Ariste: Yes. The hyperfine structure calculations only modify the number, intensity and position of the magnetic components of the lines. The combination of those components is plugged into the usual radiative transfer codes for polarized light, like DIAGONAL, which take into account the full absorption matrix, including magneto-optic effects.
A. Title: We have just seen the use of these new pattern recognition techniques in the inversion of Stokes profiles, but now you introduce the effect of hyperfine structure which was absent from any previous inversion attempt. How are those inversion codes going to tackle that?
A. López Ariste: Pattern recognition techniques, as any other inversion technique, only invert in the frame of the model that the scientist provides them. It

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Figure 6. Another example of the MnI line at 5470 Å this time in the intermediate regime in which Stokes $V$ tends to show an almost normal appearance while in Stokes $Q$ and $U$ anomalous peaks are still present.
is up to the scientist to do the science, not the computer or the inversion code. If you insist in inverting lines with hyperfine structure with models which do not take it into account, the inversion code will provide you with an answer but you will have made a mistake with your a priori model. In order to invert correctly you should provide your pattern recognition code or any other inversion code you use with the correct model, able to reproduce the observations.

References


