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Magnetic field diagnostics through the second solar spectrum: a spectroscopic analysis of the most polarizing atomic lines

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Abstract. Detailed observations of the second solar spectrum have shown a complex phenomenology whose detailed interpretation is still in a preliminary phase. The only certain thing is that the observed polarization is due to the phenomenon of resonance scattering. It is well known that such polarization can be strongly modified by the presence of a magnetic field through the so-called Hanle effect. It then follows that the second solar spectrum is, at least potentially, a fundamental instrument for diagnosing the intensity and topology of the weak magnetic fields lying in the higher layers of the solar atmosphere. Obviously, to fully exploit such potential, it is absolutely necessary to arrive at the correct theoretical interpretation, a task that has been revealed to involve many difficulties. We present an analysis of the second solar spectrum, carried out with the aim of investigating its general properties. The most interesting results concern an empirical classification of the wide variety of polarization signals that are observed, and the formulation of three empirical laws describing a series of properties common to the strongest signals.

Key words. Line: profiles – polarization – scattering – Sun: atmosphere - Sun: magnetic fields

1. Introduction

Since the spectral richness and complexity of the *second solar spectrum* (i.e. the linearly polarized spectrum of the solar radiation coming from quiet regions close to the limb) could be observed in great detail, thanks to the development of instruments with polarimetric sensitivities better than 10^{-3} (see Stenflo & Keller, 1996, 1997), many investigations have clearly pointed out the great diagnostic potential of this spectrum for the investigation of the weak magnetic fields harbored in the higher layers of the solar atmosphere (see, for example, Trujillo Bueno, 2009, and references therein). Such potential is essentially due to the fact that the linear polarization of the limb radiation, being produced by resonance scattering processes, can be strongly modified by the presence of a magnetic field not only through the well-known Zeeman effect, but also through the Hanle effect. With respect to the Zeeman effect, the Hanle effect has the advantages of being sensitive to much weaker magnetic fields (down to a few milligauss), and of being sensitive to magnetic fields showing mixed polarities within the resolution element. It is clear that in order to fully exploit the potential of this new diagnostic window, a complete and correct theoretical interpretation of the complex phenomenology shown by the second solar spectrum is absolutely needed. Unfortunately, this was quickly revealed to be an extremely complicated task, since many physical mechanisms are capable of generating and modifying the polarization of the solar radiation, and it is very difficult to properly quantify their effects in the complex environment of the solar atmosphere. Moreover, our knowledge of some of these mechanisms is still rather poor, since they have only recently received attention (e.g. evaluation of the depolarizing collisional rates, development of the theoretical framework able to account for partial redistribution effects, etc.). Because of these difficulties, up to now solar physicists have necessarily focused their attention on the analysis of particular details of the second solar spectrum, proposing models based on assumptions or approximations suitable for the interpretation of the particular polarimetric signals being studied. As a consequence, although the basic physical mechanism at the origin of the second solar spectrum (resonance scattering) is well understood, and although several important properties and peculiarities of this spectrum have already been interpreted by means of the theoretical approaches that have been proposed so far (for example, through the quantum theory of polarimetry described in Landi Degl'Innocenti & Landolfi, 2004), the interpretation of the spectrum remains rather fragmentary, and not much attention has been paid to the analysis of its general properties. As we will see in the following, there are several important open questions concerning general aspects of this spectrum that, despite their apparent simplicity, still wait to be answered.

One of the most interesting (and enigmatic) peculiarities of the second solar spectrum is that several conspicuous polarization signals are produced by spectral lines that are relatively weak in the intensity spectrum, often belonging to atomic or molecular species with low abundances (for example, the rare earth elements), whereas many strong lines in the intensity spectrum are absolutely anonymous in the second solar spectrum. Another interesting aspect, which is not yet fully understood, is the noticeable morphological difference among the observed polarization profiles. Particularly famous examples are the three-peak Q/I profiles shown by the Na I D_2 line and the Ca I line at 4227 Å, or the extremely sharp, single-peaked profile of the Sr I line at 4607 Å. Why only particular lines, of certain elements, produce strong polarization signals, and why there are such morphological differences among the various Q/I profiles, are two of the most important, general questions that need to be answered. We believe, in fact, that their solution might strongly contribute to improving our understanding of the complex physics that underlies the formation of this spectrum.

In order to answer these questions, we decided to look for properties common to all those spectral lines responsible for the strongest polarization signals of the second solar spectrum, and for other properties common to those lines with similar Q/I profiles. To this aim, we first carried out a detailed analysis of the second solar spectrum, through which we could identify, measure, and classify all the strongest polarization signals due to atomic transitions[1] (see Sect. 2). We then selected only the signals due to spectral lines free of blends in the intensity spectrum, and we analyzed their spectroscopic properties. This analysis lead us to the formulation of three empirical laws, presented in Sect. 3.

2. Analysis of the second solar spectrum

Referring to the atlas "The Second Solar Spectrum" (Gandorfer, 2000, 2002, 2005), which covers the spectral range 3160 Å – 6995 Å, we identified all the polarization signals whose Q/I amplitude exceeds a threshold value of 0.1%. To take into account the decrease of the polarization degree going towards the red part of the spectrum, we decreased this threshold value to 0.05% for wave-

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[1] Though the second solar spectrum contains many polarization signals due to molecular transitions, in this investigation we limited ourselves to the analysis of the atomic lines only.

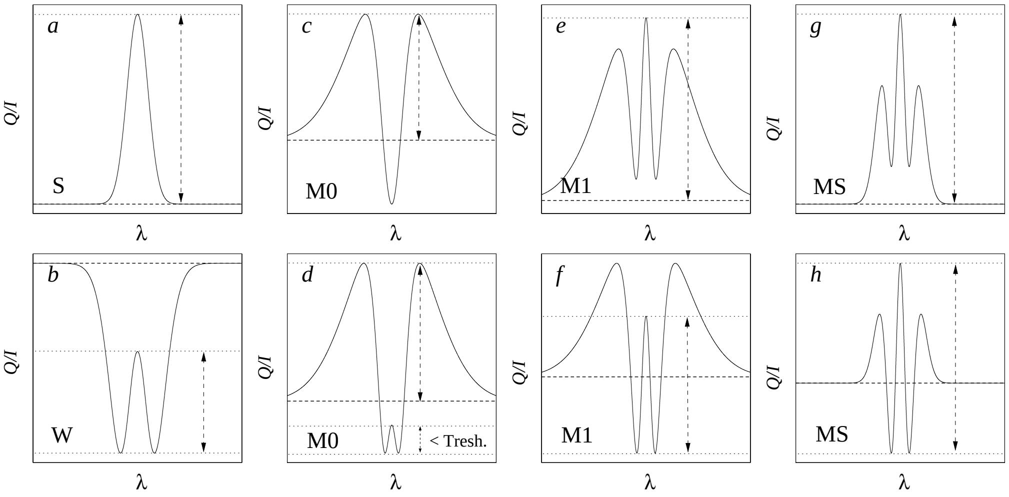

Fig. 1. Classification scheme of the Q/I profiles. In each panel, the thick horizontal dashed line represents the polarization level of the continuum, the vertical dashed line joins the limits between which the amplitude of the signals of each class has been measured.

lengths larger than 4500 Å. The threshold values, as well as the wavelength limit of 4500 Å, are completely arbitrary. Although more sophisticated selection criteria could in principle be devised, our choice seems rather reasonable, since it led us to the identification of about 250 signals, a number statistically significant and, at the same time, still easily manageable.

We divided all the selected signals into 3 classes, according to the shape of the Q/I profile. Signals showing a single sharp peak at line center have been classified as "S" signals (Fig. 1, panel *a*), those showing a depolarization (with respect to the continuum) in the wings, and a sharp peak at line center have been classified as "W" signals (Fig. 1, panel *b*), while those which show an increase of the polarization amplitude (with respect to the continuum) in the wings, followed by a depolarization approaching line center and, possibly, with a narrow peak in the core of the line, have been classified as "M" signals. The "M" signals have been further divided into three subclasses. Those which do not show any polarizing peak at line center (or that show a line-core peak whose amplitude is below the threshold value) have been classified as "M0" (Fig. 1, panels *c* and *d*), those which show polarization lobes in the wings much broader than the central peak have been classified as "M1" signals (Fig. 1, panels *e* and *f*), while those which show polarization peaks in the wings whose width is similar to that of the central peak have been classified as "MS" signals (Fig. 1, panels *g* and *h*).

We identified 248 signals, due to atomic transitions, which exceed the threshold values. Such signals have been listed in a table where we quote the wavelength, the element (or elements in the case of blends), the polarization amplitude, the morphological class (see also Fig. 2, panel *a*), as well as the equivalent width, and the reduced equivalent width of the corresponding spectral line in the intensity spectrum (as observed at disk center). This table can be found in Belluzzi & Landi Degl'Innocenti (2009). It should be noted that with the exception of the "M0" signals, which do not show any polarization peak at line center, the polarization amplitude always refers to that of the line-core peak.

As previously stated, once the strongest polarization signals of the second solar spectrum were identified, we focused our attention on the unblended signals only (158), and we took note of the most important spectroscopic properties of the corresponding spectral lines (quantum numbers, energies, Landé factors of the levels involved, Einstein coefficient for spontaneous emission, etc.). All these quantities have been quoted in a second table that can also be found in Belluzzi & Landi Degl'Innocenti (2009).

3. Formulation of three empirical laws

From the analysis of the quantities quoted in this second table, we found a series of properties common to the 158 selected signals, namely the strongest polarization signals (due to atomic transitions) of the second solar spectrum[2]. Such properties can be summarized into three empirical laws:

- **First law:** *the lower level of the transitions producing the strongest polarization signals of the second solar spectrum is either the ground level, or a metastable level*[3]*, or, alternatively, an excited level that, at the same time, is the upper level of a spectral line producing a strong polarization signal.*

Recalling that according to the terminology of spectroscopy the transitions whose lower level is either the ground level or a metastable level are referred to as *resonance transitions*, and all the other transitions as *subordinate transitions*, the first law can be reformulated as follows:

- **First law (alternative formulation):** *the transitions producing the strongest polarization signals of the second solar spectrum are either resonance transitions, or subordinate transitions whose lower level is the upper level of a resonance transition producing a strong polarization signal.*

It should be observed that only 8 signals, out of 158, are produced by subordinate transitions. There is only one exception to this law, the signal produced by the Ba ii line at 3891.8 Å. The transition responsible for this signal is, in fact, a subordinate transition, but its lower level is the upper level of two resonance transitions neither of which produces a strong polarization signal in the second solar spectrum.

- **Second law:** *All the strong polarization signals that are produced by spectral lines having a small equivalent width (i.e. lines having* $W_\lambda/\lambda < 20$ *F) are of type "S".*

This law is illustrated in Fig. 2*b*, where the signal amplitude is plotted as a function of the reduced equivalent width, and where the different symbols allow distinguishing the signals belonging to the various classes. The fact that lines with large equivalent widths produce polarization signals of type "W" or "M" strongly suggests that radiative transfer effects, and effects of partial redistribution in frequency might play an important role in the physical origin of these, more complicated, Q/I profiles. The only line with a large equivalent width that produces an "S" signal is the hydrogen line at 6563 Å (H_α). However, it should be observed that the Q/I profile of this line, though of "S" type, is somehow *sui generis*, being much broader than all the other "S" signals, and being very similar to the peculiar intensity profile of this line. It is also interesting to note that an investigation still in progress indicates that the width of the polarization peak of the "S" signals is always narrower than the width of the absorption intensity profile of the corresponding spectral line.

- **Third law:** *The spectral lines producing the strongest polarization signals* ($Q/I > 0.17\%$) *are due to transitions having either* $\Delta J = +1$ *or* $\Delta J = 0$*,* ΔJ *being defined as* $J_u - J_\ell$*.*

This law is illustrated in Fig. 2 (panels *c* and *d*). From panel *c* it can be seen that most of the selected signals are produced by transitions having either $\Delta J \equiv J_u - J_\ell = 0$ or $\Delta J = +1$ (the indices u and ℓ standing for "upper" and "lower" level, respectively). Panel *d* shows that the few signals produced by transitions with

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[2] Note that hereafter, by *strong* polarization signals we will always implicitly refer to the 158 selected signals that exceed the above mentioned threshold values.

[3] A metastable level is a level that cannot be radiatively connected with lower energy levels through allowed transitions (transitions that obey the electric dipole selection rules).

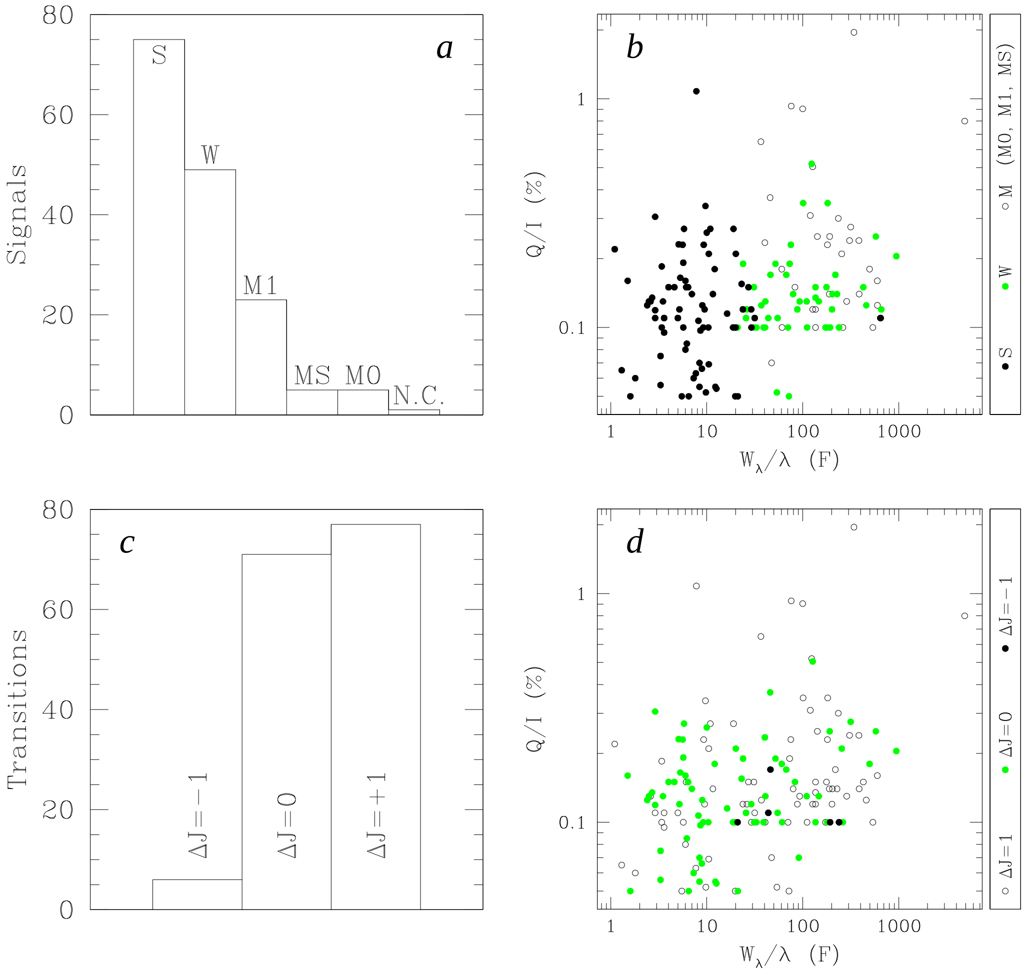

Fig. 2. *Panel a*: histogram showing the number of selected signals belonging to each morphological class. The only signal that does not fit into our classification scheme (N.C.) is the one produced by the Na I D_1 line. *Panel b*: scatter plot showing the amplitude of the signals as a function of the reduced equivalent width. The symbols allow to distinguish signals belonging to different morphological classes. *Panel c*: histogram showing the number of signals due to transitions with $\Delta J = 0, \pm 1$. *Panel d*: scatter plot showing the amplitude of the signals as a function of the reduced equivalent width. The symbols allow to distinguish signals produced by transitions with $\Delta J = 0, \pm 1$.

$\Delta J = -1$ do not have particularly large amplitudes: with the single exception of the signal produced by the Mn I line at 4034.5 Å, with an amplitude of 0.17%, all the other signals with $\Delta J = -1$ do not exceed 0.11%. Interestingly all the transitions with $\Delta J = -1$ produce "W" signals.

Another result of our analysis is that most of the selected signals are produced by transitions with $\Delta L = \Delta J$. This indicates that within the same multiplet, the strongest lines in the intensity spectrum (which, as can be demonstrated, are those with $\Delta L = \Delta J$) are those which produce the strongest polarization signals in the second solar spectrum. This latter result, combined with the third law, leads, as a sort of corollary, to a further empirical result: most of the selected signals are produced by transitions having either $\Delta L = 0$ or $\Delta L = 1$, the amplitudes of the few signals with $\Delta L = -1$ being not particularly large. Of course the quantity ΔL could be evaluated only for the transitions whose lower and upper levels are described by the *L–S* coupling scheme.

4. Conclusions

Our initial purpose of investigating the possible existence of common properties among the strongest polarization signals of the second solar spectrum has been met with success. The theoretical interpretation of the three empirical laws that have been formulated is presently ongoing. Some preliminary studies, carried out within the framework of a very simple radiative transfer model, have clearly shown how the quantum theory of polarimetry described in Landi Degl'Innocenti & Landolfi (2004) leads to results which are in very good agreement with the third law. It is important to stress that all the results that we have obtained are based on the atlas "The Second Solar Spectrum" (Gandorfer, 2000, 2002, 2005). The availability of such an atlas was an essential condition for carrying out this kind of investigation, since a set of observations made, as much as possible, with the same instrument, in similar conditions, and in a relatively short time interval (with respect to the solar activity cycle) were absolutely necessary. On the other hand, several investigations have already indicated the existence of secular variations of the second solar spectrum. In this respect, very interesting signals are produced by the Mg I b-lines. According to Gandorfer's atlas, only the line at 5167 Å ($\Delta J = 1$) produces a signal exceeding the threshold value, while the other two lines of the multiplet, at 5173 Å ($\Delta J = 0$) and at 5184 Å ($\Delta J = -1$), slightly depolarize in the wings, and show a small polarization feature in the line core. On the other hand, observations made by Stenflo and collaborators in 1995 (see Stenflo et al., 2000) show instead that all the lines of the triplet produce signals between 0.15% and 0.20% (thus exceeding our threshold value). This is an important peculiarity as far as the third rule is concerned, and clearly testifies the importance of repeating such a systematic analysis on a set of observations carried out in a different period of the solar cycle. In this sense, we believe that the results of this investigation will represent a very useful reference for any new observations of the second solar spectrum.

Another important step that should be carried out soon is the extension of this analysis to the polarization signals due to molecular bands which are seen to dominate the second solar spectrum in several spectral intervals.

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