A spectroscopic analysis of the most polarizing atomic lines of the second solar spectrum[★]

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ABSTRACT

We present an analysis of the second solar spectrum, as plotted in graphical form in the three volumes of the atlas “The Second Solar Spectrum”, in the wavelength range between 3160 Å and 6995 Å. All the strongest positive linear polarization signals produced by atomic spectral lines are identified, and their amplitudes are listed, along with the most relevant spectroscopic properties of the lines. The various signals are divided into five classes according to the shape of their Q/I profiles. Three empirical rules are formulated from the analysis of the amplitude and shape of the various signals, and of the spectroscopic properties of the spectral lines.

Key words. atomic data – line: profiles – polarization – scattering – Sun: atmosphere

1. Introduction

The theoretical interpretation of the “second solar spectrum”, namely the linearly polarized spectrum of the solar radiation coming from the quiet solar atmosphere close to the limb, is presently one of the most interesting topics in solar physics. The term second solar spectrum, first suggested by Ivanov, is indeed appropriate since this spectrum has a structural richness that can be compared to that of the intensity spectrum, and, at the same time, it shows a significantly different aspect. The first detection of a linear polarization signal in a spectral line observed close to the solar limb (Ca I at 4227 Å) dates back to 1941 (Redman 1941). After Redman’s discovery, other strongly polarizing lines were detected during the 1960s and 1970s (Brückner 1963; Stenflo 1974; Wiehr 1975, 1978). The first systematic analysis was performed by Stenflo and collaborators in the 1980s (Stenflo et al. 1980, 1983a,b), though with instruments of reduced polarimetric sensitivity. Most of the spectral structures of the second solar spectrum therefore remained inaccessible until about one decade ago, when the first instruments capable of performing observations with polarimetric sensitivities better than 10^{-3} were developed (Stenflo & Keller 1996, 1997). Today the second solar spectrum is available in graphic form in the atlas “The Second Solar Spectrum” (Gandorfer 2000, 2002, 2005), which covers the spectral range between 3160 Å and 6995 Å.

It was soon realized that the second solar spectrum provides a new formidable window for diagnosing the Sun. Its interpretation, which represents an extraordinary theoretical challenge, seems to be a necessary and unavoidable step to improve our knowledge of the solar atmosphere. Although the fundamental physical process at the origin of the second solar spectrum (resonance scattering) is well understood, the formulation of a complete theory, able to describe the generation and transfer of polarized radiation in such a complex environment as the solar atmosphere, has revealed to be an extremely complex

task. Today, we can rely on a rigorous theory of the polarization in spectral lines which has been deduced from the principles of quantum electrodynamics (see the monograph by Landi Degl’Innocenti & Landolfi 2004). Through the application of this theory, combined with the development of suitable numerical methods in polarized radiative transfer (Trujillo Bueno 2003a; Manso Sainz & Trujillo Bueno 2003), it has been possible to interpret several important features of the second solar spectrum, and to start exploiting it to investigate the physical properties of our nearest star (see Trujillo Bueno 2009, for a recent review).

The interpretation of the second solar spectrum through the above mentioned theory, as well as through other theoretical approaches that have been proposed is, however, still rather fragmentary. The reason is that, as previously observed, the problem we are facing is very complex, and either the approaches based on simplifying assumptions (last scattering approximation, flat spectrum approximation, two-level atom, unpolarized lower level, etc.), or the more sophisticated ones including detailed radiative transfer cannot be applied with success to whatever spectral line. As a consequence, most of the investigations have been dedicated to the interpretation of particular lines or multiplets of this spectrum, while not much attention has been paid to the analysis of its general properties.

In this respect, probably one of the most important questions concerning the whole second solar spectrum, that still waits for an answer, is why only particular lines, of certain elements, produce strong polarization signals. For instance, one can wonder why some elements are particularly present with their lines in the second solar spectrum, whereas other elements of comparable abundance are totally absent. Moreover, observing the second solar spectrum one can easily realize that several conspicuous polarization signals are produced by relatively weak lines in the intensity spectrum, often belonging to atomic or molecular species with low abundances. On the other hand, many strong lines in the intensity spectrum are quite anonymous in the second solar spectrum. At the moment it is difficult to explain in

[★] Tables 1 and 2 are only available in electronic form at <http://www.aanda.org>

a quantitative way such peculiarities, and to predict which lines are expected to produce particularly strong polarization signals, though, when dealing with single spectra, interesting and encouraging, even if qualitative, results have been obtained for Ti I (Manso Sainz & Landi Degl’Innocenti 2002), and Ce II (Manso Sainz et al. 2006), two of the most remarkable elements of the second solar spectrum.

In this paper we present an investigation carried out over the whole second solar spectrum as plotted in graphical form in the three volumes of the atlas “The Second Solar Spectrum” (Gandorfer 2000, 2002, 2005). The aim is to try to answer the previous question, looking for possible general physical properties common to all the most polarizing atomic spectral lines. The first part of the investigation has been dedicated to a complete analysis of the spectrum, through which we could identify, measure and classify all the strongest polarization signals due to atomic transitions (Sect. 2). We then selected only the atomic spectral lines of unambiguous identification and free of blends, and we analyzed their spectroscopic properties (Sect. 3). This analysis lead us to the formulation of three empirical rules presented in Sect. 4. In Sect. 5 we tried to interpret some of the rules within the framework of the theory presented in Landi Degl’Innocenti & Landolfi (2004).

2. Analysis of the second solar spectrum

We analyzed the second solar spectrum as observed by Gandorfer (2000, 2002, 2005) between 1999 and 2003 using the Zürich Imaging Polarimeter (ZIMPOL) at the Gregory Coudé Telescope of IRSOL (Vols. I and II), and at the McMath-Pierce telescope of Kitt-Peak (Vol. III), in the spectral range between 3160 Å and 6995 Å. We decided to refer to these data since the main aim of our investigation was to analyze the full second solar spectrum, and it was therefore essential to refer to a set of homogeneous observations obtained, as much as possible, with the same instrument, and in a relatively short time interval (with respect to the solar activity cycle). However, it is important to point out that several signals that are not so conspicuous in Gandorfer’s atlas, turned out to be much stronger in other observing runs, made in different periods of the activity cycle¹.

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. We then identified all the atomic spectral lines producing positive linear polarization signals (according to the specifications better defined in Sect. 2.2) with an amplitude larger than 0.1%. To take into account the decrease of the polarization degree, both in the continuum and in the spectral lines, going towards the red part of the visible spectrum, this threshold value has been decreased to 0.05% for wavelengths larger than 4500 Å. These threshold values for the Q/I signal amplitude, as well as the wavelength limit of 4500 Å, are completely arbitrary. Although more sophisticated criteria could in principle be applied, our choice seems in any case to be quite reasonable: in the analyzed spectral range, in fact, about 250 lines producing polarization signals higher than the threshold values can be identified. This number is statistically significant and, at the same time, still easily manageable.

¹ A particularly relevant example is the one of the Mg I b-lines. The polarization signals observed in these lines by Stenflo and collaborators in 1995 (see Stenflo et al. 2000) are significantly different from those of Gandorfer’s atlas.

2.1. Classification of the Q/I signals

We divided all the selected signals into three main classes, according to the shape of the Q/I profile. The signals which show a Q/I profile with a single peak at line center have been classified as “S” signals (see Fig. 1, panel a), those which depolarize in the wings, and produce a narrow peak at line center have been classified as “W” signals (see Fig. 1, panel b), while those that polarize in the wings, show a decrease of the polarization amplitude approaching to the line-core and, eventually, show a narrow peak at line center have been classified as “M” signals. The “M” signals have been further divided into three subclasses, according to the presence or not of the line-core peak, and according to the relative width of the wing-lobes with respect to the line-core peak (if present). The “M” signals which do not show any polarizing peak at the line-core (or that show a weak line-core peak, with an amplitude below the threshold value) have been classified as “M0” (see Fig. 1, panels c and d), those which show in the wings polarization lobes much broader than the line-core peak have been classified as “M1” (see Fig. 1, panels e and f), while those which show in the wings polarization peaks whose width is similar to, or smaller than, the width of the line-core peak have been classified as “MS” (see Fig. 1, panels g and h). As far as “M1” and “MS” signals are concerned, our classification scheme does not take into account whether the line-core peak exceeds or not the continuum level or the wing-lobe amplitude. We have to remark that the classification of the signals through these criteria can be quite ambiguous in some cases. However, we believe that the scheme presented in this paper can be considered as a good starting point to organize in a few significative classes the wide variety of polarimetric signals that are found in the second solar spectrum. Examples of signals of the second solar spectrum belonging to the various classes proposed can be found in Fig. 2.

Some “S” signals lie on the large wings of strongly depolarizing lines. In these cases, if the peak does not reach the theoretical continuum, it is not trivial to understand if we are in the presence of a polarizing spectral line or not. Indeed, if the line is intrinsically “neutral”, or less depolarizing than the wings of the strong line, the resulting peak would be nothing but a kind of an “artefact” (see Fig. 3, panel a). In this respect, important hints can be obtained from the analysis of other possible blends present in the same depolarizing wings. For example, if all the blended lines produce polarization peaks, and these are very similar to each other, very likely their polarization effect is only apparent, and they have not been taken into account. On the other hand, if we are in the presence of such a blend, and there are reasons to believe that the polarization signal is “real”, then it has been classified as “S”.

At wavelengths shorter than 4000 Å, the solar spectrum is crowded by a large number of very intense spectral lines, usually strongly blended between each other. A significant number of these strong lines produce in the second solar spectrum strong polarization signals, which very often overlap. This peculiarity makes our investigation rather difficult in this spectral region. On one hand, in fact, it is not unusual to find interesting polarization signals strongly blended with the large wings of these lines, and in these cases it can be quite difficult to classify the shape of the signals, and to decide whether or not they exceed the threshold value. In several cases we tried to justify our conclusions with a note in Table 1 (see Sect. 2.3). On the other hand, the classification of the polarization signals produced by the same strong lines is in some cases rather difficult. If they are isolated, in the sense that their extended wings are not blended with other

Fig. 1. Classification scheme of the Q/I profiles. The thick dashed horizontal line represents the continuum level. The vertical dashed line joins the limits between which the amplitude of the signal has been measured.

Fig. 2. Examples of signals of the second solar spectrum belonging to the various classes proposed. Panel **a**): Sr I at 4607 Å (S signal); panel **b**): Fe I at 4415 Å (W signal); panels **c**) and **d**): Co I at 3405 Å and Ti II at 3373 Å (M0 signals), panels **e**) and **f**): Ca I at 4227 Å and Fe I at 4046 Å (M1 signals); panels **g**) and **h**): Sr II at 4078 Å and Cr I at 5208 Å (MS signals). The observations shown in this figure have been scanned from the atlas “The Second Solar Spectrum” (Gandorfer 2000, 2002, 2005).

Fig. 3. Examples of polarization signals blended with stronger and broader ones. Panel **a**): a S^* signal. Panel **b**): amplitude measurement of a S signal blended with the blue wing of a stronger one.

strong lines belonging to the same multiplet, then the signals can be usually classified following the proposed scheme (usually as “M0” or “M1”). On the contrary, if blends between strong lines of the same multiplet are present, then in the far wings of the lines the polarization is mainly due to quantum interferences between different J -levels (see for example the H and K lines of Ca II), and the resulting profiles might not fall in one of the classes proposed.

2.2. Measurement of the signal amplitude

With the exception of the “M0” lines, what has been measured and compared to the threshold value is the amplitude of the line-core peak. We believe, in fact, that this quantity contains the most interesting physical information. Moreover, it is rather uncommon for this peak to be severely affected by blends, since it falls at line center. As far as the “S” signals are concerned, the amplitude of the peak is measured from the continuum level which is plotted in the atlas (see Fig. 1, panel a). We recall that this quantity is not directly observed, but it is deduced from the theoretical calculations of Fluri & Stenflo (1999), for $\lambda > 4000$ Å, and of Stenflo (2005) for $\lambda < 4000$ Å. On the other hand, as far as “W” signals are concerned, the amplitude of the peak is measured from the lowest depolarizing dip (see Fig. 1, panel b). Concerning the “M1” and “MS” signals, the choice of the reference level from which the line-core peak amplitude is measured depends on whether the polarization at the lowest depolarizing dip is below the theoretical continuum or not. In the former case it is measured from the lowest depolarizing dip (see Fig. 1, panels f and h), in the latter from the theoretical continuum (see Fig. 1, panels e and g). As far as the “M0” signals are concerned, what has been measured, and compared to the threshold value, is the amplitude of the wing-lobes with respect to the theoretical continuum (see Fig. 1, panels c and d). It is important to note that this quantity has to be considered with caution. The wing-lobes, in fact, are usually very broad, and often the presence of blends makes impossible the estimate of their real amplitude. For the sake of completeness, also for the “M1” and “MS” signals the amplitude of the wing-lobes has been measured and listed in Table 1 (see Sect. 2.3) below the amplitude of the line-core peak.

In the case of blends, the unblended (or less blended) left or right dip (or lobe) has been considered. The amplitude of any “S” signal blended with a stronger (polarizing or depolarizing) signal is not measured from the theoretical continuum of the atlas, but from a reference value qualitatively estimated from the expected shape of the Q/I profile of the blending line (see Fig. 3, panels a and b).

2.3. Table of the most polarizing atomic spectral lines of the second solar spectrum

In Table 1 we list, in order of increasing wavelength, all the atomic spectral lines that produce positive polarization signals higher than the threshold value (0.1% if $\lambda < 4500$ Å, or 0.05% if $\lambda \geq 4500$ Å), as explained in detail in Sect. 2. In the first four columns we list the wavelength (in Å), the element (elements in the case of unresolved blends), the equivalent width (in mÅ), and the reduced equivalent width (in Fraunhofer). All these quantities have been taken from Moore et al. (1966). In the case of blends the same notation as in this reference monograph has been used: if one component of a blend dominates with respect to the other components, its chemical symbol is preceded by “/”, if it contributes more than the others, it is preceded by “/”. If one component is completely hidden by the others, its chemical symbol is written in brackets. If two or more components are separated by a dash, this means that the first one falls at a shorter wavelength than the second one. If there is only one component preceded or followed by a dash, this indicates that the line is probably a blend, the other unknown contributor being, respectively, at a shorter or longer wavelength. A “p” following the chemical symbol indicates that the spectral line is “predicted” from known atomic energy levels, but it has not been observed in the laboratory yet. An asterisk over the numerical value of the equivalent width means that it is referred to the blend of two or more lines, one of which is the one under investigation. The reduced equivalent width is known for all the selected lines but one (Ba I at 5535.51 Å), and it is often derived through theoretical procedures (see Moore et al. 1966, for details).

In the next 3 columns we list the value of the amplitude of the polarization signal (in percent), giving the values of $(Q/I)^M$, $(Q/I)^m$, and the difference $Q/I = (Q/I)^M - (Q/I)^m$. The quantities $(Q/I)^M$ and $(Q/I)^m$ are the values of (Q/I) measured at the top and at the bottom of the polarization signal, respectively. As far as “S” signals are concerned, an asterisk over the value of $(Q/I)^m$ indicates that this reference polarization value is not the theoretical continuum plotted in the atlas, but a value estimated by the authors as previously described, because of the presence of a blend. In the case of “M1” and “MS” signals we list both the amplitude of the line-core peak (which is the quantity we will refer to throughout our investigation) and below, for the sake of completeness, the amplitude of the wing-lobes. This last quantity has not been listed in the case of severely blended wing-lobes. Note that the amplitude of the wing-lobes, both for the “M0” signals, and for the “M1” and “MS” signals, has been quoted in italic. These three quantities, as explained, have been measured graphically on the three volumes of the atlas “The Second Solar Spectrum” (Gandorfer 2000, 2002, 2005). Finally, in the last column we quote the classification of the Q/I profile, according to the scheme described in Sect. 2.1. Several notes have been added with the aim of clarifying either our classification, or the Q/I measurement, in the case of blended signals, and in order to point out peculiarities that have been noticed in several profiles during our analysis.

3. Selection of the Lines

Once the polarization signals exceeding the threshold value have been identified, classified, and listed in Table 1, we concentrated only on those produced by spectral lines free of blends in the intensity spectrum, and with unambiguous classification and

amplitude measurement (signals free of blends in the Q/I spectrum). These lines are collected, element by element, in Table 2.

In the first six columns of Table 2 we list the element, the solar and laboratory wavelengths, the reduced equivalent width, the Q/I signal amplitude, and the classification of the Q/I signal. With the exception of the laboratory wavelengths, which are taken from Moore (1945)², all the other quantities are the same as in Table 1. As far as “S” signals are concerned, an asterisk over the Q/I value indicates that the amplitude of the peak has not been measured from the theoretical continuum, but from another reference value because of the presence of a blend, as explained in detail in Sect. 2.2.

In the next two columns we list the lower and upper terms of the transition, the multiplet number, and the J -values of the lower and upper levels of the transition. These quantities are taken from Moore (1945)². In column nine we list the Einstein coefficients for spontaneous emission. These quantities are taken either from Ralchenko et al. (2008) or from Kurucz & Bell (1995), depending on which database quotes the more recent work.

In the next four columns we list the energies and the Landé factors of the lower and upper levels. These values, as well as the percentage of the coupling scheme listed in the last column, are taken from Moore (1949, 1958, 1971), and from Martin et al. (1978). The only exception are the hydrogen lines. In these cases the energies, which are the average values over the fine structure, are taken from Kurucz & Bell (1995). An asterisk over the Landé factor indicates that the value is not the experimental one, but is calculated theoretically under the hypothesis of $L-S$ coupling. As far as hydrogen is concerned, it has been demonstrated that the Landé factor of all its levels is equal to 1 (Casini & Landi Degl’Innocenti 1994). In the following column we specify if the lower level is the ground level (GL), a metastable level (ML), or a level that, at the same time, is the upper level of a transition that produces a polarization signal entering our threshold values (PL). A question mark (PL?) means that the lower level is the upper level of a transition producing a spectral line that falls outside the wavelength interval covered by the atlas, but for which there are hints to believe that it might produce a strong signal in the second solar spectrum. A short dash in this column means that the lower level does not enter any of these three classes (there is just one line of this kind). Hereafter, following the conventions of spectroscopy, the transition whose lower level is the upper level of another transition, will be referred to as a “subordinate transition”, while the transition whose lower level is the ground level, or a metastable level, will be referred to as a “resonance transition”. A level is considered metastable if it cannot be connected through an allowed transition (according to the selection rules in the $L-S$ coupling scheme) to a lower level, in other words, if there are no lower levels showing opposite parity, and satisfying the selection rules $\Delta\ell = \pm 1$, $\Delta S = 0$, $\Delta L = 0, \pm 1$, $0 \rightarrow 0$, $\Delta J = 0, \pm 1$, $0 \rightarrow 0$. The lower level of five Ce II lines (the first four lines, and the last line of this ion listed in Table 2) is not metastable according to the previous definition. For these levels, however, $L-S$ coupling holds only approximately, and the allowed transitions towards lower levels fall in the infrared part of the spectrum, at wavelengths larger than 20 000 Å (11 500 Å as far as the level at 11 015.579 cm⁻¹ is concerned). Unfortunately there are no data concerning the transition probabilities and the relative intensities of these infrared lines, but we believe that it should be rather correct to consider

Table 3. Lines of Table 2 produced by subordinate transitions, and corresponding resonance lines.

El.	Subordinate trans.			Resonant trans.		
	λ (Å)	Q/I (%)	type	λ (Å)	Q/I (%)	type
H I	4340.475	0.12	W	1216 [Ly α]		outside
	6562.808	0.109	S	1216 [Ly α]		atlas range
Mg I	5528.418	0.052	W	2852		outside
	4703.003	0.050	W	2852		atlas range
Ca II	3179.342	0.35	W	3933.682	0.90	M1
Fe I	6024.068	0.05	S	4045.825	0.390	M1
Cu I	5218.209	0.052	S	3247.540	0.93	M0
Ba II	4130.657	0.28	S	4554.036	0.65	MS

these levels metastable as well. Finally, in the last column we list, when available, the percentage of the coupling schemes of the upper and lower terms given in column seven. We recall that light elements are usually well described by the $L-S$ coupling scheme. For the sake of completeness, if a signal, that has not been selected (because of blends in the intensity spectrum or in the second solar spectrum), is produced by a transition that belongs to a multiplet already present in Table 2, this transition has been listed in italic fonts in the same table.

4. Results

In the spectral range between 3190 Å and 6995 Å, we could identify 248 polarimetric signals, due to atomic transitions, that exceed the threshold value. The signals that can be unambiguously associated to a particular transition (no blends in the intensity spectrum), and that can be unambiguously classified and measured (no blends in the second solar spectrum) are 158. Hereafter we will always refer only to these lines (listed in roman fonts in Table 2).

Our analysis allows establishing some empirical laws. The first one can be stated as follows. *Rule 1: The lower level of the transitions corresponding to the 158 lines listed in Table 2, namely the most prominent lines of the second solar spectrum, is either the ground level or a metastable level (in the sense specified above) or, alternatively, the upper level of a resonance transition corresponding to a line also contained in the same table. In other words, all the lines of Table 2 are either resonance lines, or subordinate lines sharing their lower level with the upper level of a resonance line producing a strong polarization signal.* This rule has only one exception, the Ba II line at 3891.781 Å. The lower level of the corresponding transition ($6p\ ^2P_{1/2}^o$), in fact, is the upper level of the transition corresponding to the Ba II D₁ line at 4934.095 Å, which shows a depolarization feature in the atlas of Gandorfer (2000), and of the transition $5d\ ^2D_{3/2}-6p\ ^2P_{1/2}^o$ at 6496.908 Å, which is a weakly polarizing line (see Gandorfer 2000).

Without considering the above mentioned Ba II line, only eight lines of Table 2 are produced by subordinate transitions. As stated in Rule 1, the lower level of these transitions is always the upper level of a resonance one. Subordinate lines, and their corresponding resonance lines are listed in Table 3. In four cases the corresponding resonance transition produces a polarization signal included in Table 2, in four cases it falls outside the spectral interval covered by the three volumes of the atlas. These are the Ly α H I line at 1216 Å, and the Mg I resonance line at 2852 Å ($^1S_0-^1P_1$). Although the second solar spectrum of these two lines has not been observed yet, it is expected that they

² The data for the Nb II and the Dy II lines are taken from Kurucz & Bell (1995).

Fig. 4. Histograms showing: **a)** the number of signals in each class; **b)** the number of transitions with $\Delta J = \pm 1, 0$; **c)** the number of transitions with $\Delta L = \pm 1, 0$; and **d)** the number of transitions with $\Delta J - \Delta L = \pm 2, \pm 1, 0$. The unresolved fine structure transitions are not included in the histogram of panel **b)** (H I lines, and Mg I lines at 3832.310 Å, and 3838.302 Å). The transitions between terms that are not described within the $L - S$ coupling scheme are not included in the histogram of panel **c)**. The transitions excluded from the histograms of panels **b)** and **c)** are also excluded from the histogram of panel **d)**.

might produce strong polarization signals. In particular, as far as the Mg I line is concerned, this conclusion comes from the fact that Ca I, Sr I, and Ba I (elements belonging to the Mg I isoelectronic sequence) all show a transition $^1S_0 - ^1P_1$, which produces a strong polarization signal in the second solar spectrum (see Table 2). Note in particular that the Ca I line (4226.740 Å), and the Sr I line (4607.338 Å) produce two of the strongest polarization signals of the second solar spectrum. A detailed analysis of the second solar spectrum of the alkali metals and of the alkali earths metals (and of the ions belonging to their isoelectronic sequences) will be the subject of a future investigation. In the following subsections we discuss some general results concerning the classification of the polarization signals, and the quantum numbers of the corresponding transitions. The results are presented in the form of histograms and scatter plots in Figs. 4 and 5.

4.1. Q/I profile classification

From Fig. 4 (panel a), it can be observed that most of the signals are of type “S” and of type “W”. The only signal that does not fit into our classification scheme is the one produced by the Na I D_1 line at 5895.940 Å. Plotting the signal amplitude as a function of the reduced equivalent width, and distinguishing through different colors the various classes (see Fig. 5, panel a), a second empirical rule can be established. *Rule 2: all the signals produced by the spectral lines of Table 2 having a small equivalent width (i.e. lines having $W_\lambda/\lambda < 20 F$) are of type “S”.* The only line, with a large reduced equivalent width, that produces in the second solar spectrum an “S” signal is the hydrogen line at 6563 Å (H_α). This line, however, has to be considered with caution within our sample of lines. Its Q/I “S” profile, in fact, is much broader than all the other “S” signals, and also its intensity profile is quite peculiar. The fact that lines having high values of the equivalent width show profiles of the type “W” or “M”, suggests that for these lines transfer effects and partial redistribution effects play an important role.

4.2. Quantum numbers

Among the 158 selected lines, a reduced number (18) correspond to transitions which do not satisfy the selection rule $\Delta S = S_u - S_\ell = 0$ (the indices u and ℓ meaning “upper” and “lower”), while 2 correspond to transitions which do not satisfy the selection rule $\Delta L = L_u - L_\ell = 0, \pm 1, 0 \rightarrow 0$. These lines are listed in Table 4. Note that as far as rare earth elements are concerned, the

Table 4. Transitions breaking the $\Delta S = 0$ and the $\Delta L = 0, \pm 1, 0 \rightarrow 0$ rules.

Elem.	λ (Å)	ΔS	A (10^7 s^{-1})	Type
Ti I	5565	-1	1.41	S
	4778	-1	1.96	S
V II	3592	1	4.41	W
Fe I	3521	-1	0.28	W
	3570	-1	6.76	M1
	4384	1	5.00	M1
	4405	1	2.75	M1
	4415	1	1.18	W
	6024	1	1.27	S
Ni I	3625	1	0.026	W
	3602	1	0.044	W
	3453	1	0.98	W
	3462	1	2.70	W
	3674	1	0.20	W
	3485	-1	3.38	S
Ce II	4223	-1	1.87	S
Nd II	4463	1	2.46	S
Dy II	3695	1	2.59	S
Elem.	λ (Å)	ΔL	A (10^7 s^{-1})	Type
Ni I	3664	-2	0.20	W
	3485	2	3.38	S

terms involved in the transitions cannot be described following exactly the $L - S$ coupling scheme (see Table 2).

As it can be observed from panel b of Fig. 4, most of the signals are produced by transitions with $\Delta J = J_u - J_\ell = 0$ or $\Delta J = +1$. The six most polarizing lines, in particular, have $\Delta J = +1$, while the lines with $\Delta J = -1$ (six lines, all falling at wavelengths shorter than 4500 Å) produce in general weak polarization signals, close to the threshold value (see Fig. 5, panel b; note that two points, corresponding to the Ni I lines at 3492.9 Å, and 3380.6 Å, perfectly overlap so that only five red points can be observed). With the only exception of the Mn I line at 4034.5 Å, whose polarization signal reaches an amplitude of 0.17%, all the other lines with $\Delta J = -1$ produce signals that do not exceed 0.11%. A third empirical rule can then be stated as follows. *Rule 3: the lines of Table 2 showing 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 $J_u - J_\ell$.* Note finally that all the transitions with $\Delta J = -1$ produce “W” signals.

From panel c of Fig. 4, it can be observed that most of the signals correspond to transitions having either $\Delta L = +1$ or $\Delta L = 0$. The few transitions with $\Delta L = -1$ produce in general

Fig. 5. In the first three graphs (from left to right and from top to bottom) the amplitude of the selected signals is plotted as a function of the reduced equivalent width. The different colors allow distinguishing the signals belonging to the various classes (panel a)), corresponding to transitions with different ΔJ (panel b)), and to transitions with different ΔL (panel c)). The lines excluded from the histograms of panels b) and c) of Fig. 4 have been excluded as well from the plots of panels b) and c). In panel d) the signal amplitude is plotted as a function of the quantity W_2 (see Eq. (2) for its definition). The black dashed line has a slope of 0.011: all the points lie either close to this line, or below it. In panel e) the ratio $(Q/I)/W_2$ is plotted as a function of wavelength. The black dashed line represents the best linear fit to the points, and shows a decreasing trend with wavelength. In panel f) the same quantity is plotted as a function of the reduced equivalent width. In the last three graphs only the “S” signals (with exception of the H_α line), with metastable (or fundamental) lower level, and with the upper and lower levels described by the $L - S$ coupling scheme (see footnote 3) have been considered. The intensity of the critical magnetic field (see text) is represented through a color scale.

rather weak polarization signals (see Fig. 5, panel c). In the next section we will try to justify this empirical result within the theoretical framework presented in Landi Degl'Innocenti & Landolfi (2004).

Finally, panel d of Fig. 4 shows that most of the signals are produced by transitions with $\Delta L = \Delta J$. This seems to be due to the fact 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 linear polarization signals in the second solar spectrum.

5. Theoretical considerations

In this section we try to interpret some aspects of the results presented above within the framework of the theory presented in Landi Degl'Innocenti & Landolfi (2004). Since most of the selected lines belong to multiplets, the two-level atom approximation cannot be applied. We consider therefore a two-term atom with unpolarized lower term. If we neglect collisions, and we assume that no magnetic field is present, it can be demonstrated (see Sect. 10.17 of Landi Degl'Innocenti & Landolfi 2004) that in the neighborhood of a particular line the explicit expression of the emission coefficient in the four Stokes parameters is

$$\varepsilon_i = k_M^A S^{J_\ell, J_u} \phi(v_{\beta_u L_u S J_u, \beta_\ell L_\ell S J_\ell} - \nu) \sum_{KQ} W_K(L_\ell L_u S, J_\ell J_u) \quad (1)$$

$$\times (-1)^Q \mathcal{T}_Q^K(i, \Omega) J_Q^K(v_{\beta_u L_u S, \beta_\ell L_\ell S}) \quad \text{with } (i = I, Q, U, V),$$

where the product $k_M^A S^{J_\ell, J_u}$ is the frequency integrated absorption coefficient relative to a single line of the multiplet, ϕ is the line profile, $\mathcal{T}_Q^K$ is a geometrical tensor, J_Q^K is a tensor which describes the radiation field illuminating the atomic system, and finally

$$W_K(L_\ell L_u S, J_\ell J_u) = (-1)^K \frac{\begin{Bmatrix} 1 & 1 & K \\ J_u & J_u & J_\ell \end{Bmatrix} \begin{Bmatrix} 1 & 1 & K \\ L_u & L_u & L_\ell \end{Bmatrix} \begin{Bmatrix} L_u & L_u & K \\ J_u & J_u & S \end{Bmatrix}}{\begin{Bmatrix} 1 & 1 & 0 \\ J_u & J_u & J_\ell \end{Bmatrix} \begin{Bmatrix} 1 & 1 & 0 \\ L_u & L_u & L_\ell \end{Bmatrix} \begin{Bmatrix} L_u & L_u & 0 \\ J_u & J_u & S \end{Bmatrix}}. \quad (2)$$

Note that Eq. (1) is obtained assuming that the radiation field tensor, J_Q^K , has the same value for all the transitions of the multiplet. We consider a plane-parallel model of the solar atmosphere, and we take a Cartesian reference system with the z axis (the quantization axis) directed along the vertical. Under this approximation the radiation field illuminating the atomic system has cylindrical symmetry about the vertical, and can be fully described through only two components of the radiation field tensor: J_0^0 , and J_0^2 . The former describes the average intensity of the radiation field over all the directions of propagation, the latter gives a measure of its anisotropy. The anisotropy degree of the radiation field is usually quantified through the so-called anisotropy factor, a dimensionless parameter defined as $w = \sqrt{2} (J_0^2 / J_0^0)$.

Taking the reference direction for positive Q parallel to the atmosphere, the only non zero radiative transfer coefficients are η_I , η_Q , ε_I and ε_Q , where η_I and η_Q are the absorption coefficients in the Stokes parameters I and Q , respectively (see Landi Degl'Innocenti & Landolfi 2004, Eqs. (7.47a-e)). The radiative transfer equations take therefore the simpler form

$$\frac{d}{ds} \begin{pmatrix} I \\ Q \end{pmatrix} = - \begin{pmatrix} \eta_I & \eta_Q \\ \eta_Q & \eta_I \end{pmatrix} \begin{pmatrix} I \\ Q \end{pmatrix} + \begin{pmatrix} \varepsilon_I \\ \varepsilon_Q \end{pmatrix}. \quad (3)$$

Since the anisotropy degree is small in the solar atmosphere, we have $\eta_Q \ll \eta_I$ and $\varepsilon_Q \ll \varepsilon_I$, and we can proceed by a perturbative

approach. In the limit of a tangential observation at the limb we have

$$\frac{d}{ds} I(\nu, \Omega_{\parallel}) = \frac{d}{ds} Q(\nu, \Omega_{\parallel}) = 0, \quad (4)$$

and, after some algebra, we obtain (Trujillo Bueno 2003b; Landi Degl'Innocenti & Landolfi 2004)

$$\frac{Q}{I} = \frac{\varepsilon_Q(\nu, \Omega_{\parallel})}{\varepsilon_I(\nu, \Omega_{\parallel})} - \frac{\eta_Q(\nu, \Omega_{\parallel})}{\eta_I(\nu, \Omega_{\parallel})}. \quad (5)$$

Since we are considering a two-term atom with unpolarized lower term, we have $\eta_Q = 0$, and by substitution of Eq. (1) into Eq. (5), we obtain the relation

$$\frac{Q}{I} \approx \frac{\varepsilon_Q}{\varepsilon_I} = \frac{3}{4} \mathcal{W}_2. \quad (6)$$

The quantity $\mathcal{W}_2 \equiv W_2(L_\ell L_u S, J_\ell J_u)$, which is obtained from Eq. (2), setting $K = 2$, is the generalization to the case of a two-term atom of a similar quantity defined for a two-level atom, which is often referred to as “polarizability factor”.

Equation (6) shows that, under the simplifying hypotheses introduced above, the fractional polarization is proportional to the product of the anisotropy factor and of the quantity $\mathcal{W}_2$, which depends on the quantum numbers of the transition. Figure 6 shows the values of $\mathcal{W}_2$ for a certain number of transitions. We can easily observe that the higher values, are found for transitions with $\Delta L = +1, 0$, and with $\Delta J = \Delta L$, independently of the spin value, in agreement with the empirical results obtained from our analysis of the second solar spectrum.

Since we are neglecting radiation transfer effects, and since the theory we are applying neglects partial redistribution effects, we consider hereafter only the lines with small equivalent width, for which these effects should be small, or negligible. We consider therefore only the “S” signals (the corresponding lines have $W_\lambda/\lambda < 30$ F, see Fig. 5, panel a), with the exception of the H_α line (see Sect. 4.1). Recalling that the theory we are applying is based on the assumption that the atomic system is described by the $L - S$ coupling scheme, and recalling the hypothesis of the unpolarized lower term, we restrict from now on to consider only the “S” signals due to transitions between levels in $L - S$ coupling³, with a metastable (or fundamental) lower level.

Plotting the signal amplitude as a function of $\mathcal{W}_2$, we observe that all the points lie either close to the straight line passing through the origin, and having slope equal to 0.011, or below it (see Fig. 5, panel d). According to Eq. (6), this behavior implies that the anisotropy factor w has to be smaller than $(4/3) \times 0.011 \approx 0.015$. Since the anisotropy factor of the photospheric continuum, around 4000 Å, is of about 0.15, we immediately notice that there is a discrepancy of about one order of magnitude⁴. Very likely, such a significant discrepancy is due to the fact that in Eq. (6) three fundamental “ingredients”, all expected to decrease the polarization, are neglected: the magnetic field, collisions, and radiation transfer effects.

The effect of a unimodal microturbulent magnetic field can be taken into account rather easily. In the presence of such a magnetic field, in fact, Eq. (6) is modified into

$$\frac{Q}{I} \approx \frac{3}{4} \mathcal{W}_2 w \frac{1}{5} \left(1 + \frac{2}{1 + H_u^2} + \frac{2}{1 + 4H_u^2} \right), \quad (7)$$

³ As far as rare earth elements are concerned, if the percentage of the $L - S$ coupling of the upper or lower level is unknown, or smaller than 70% (see Table 2), the line has been discarded.

⁴ The value of 0.15 refers to the “solar surface”, as defined in Sect. 12.3 of Landi Degl'Innocenti & Landolfi (2004).

Fig. 6. Values of $\mathcal{W}_2$ (see Eq. (2) for its definition) for different transitions. Each panel refers to a particular spin value. Within each panel the various boxes refer to a couple of values for L (L_ℓ on the horizontal axis, and L_u on the vertical axis). Within each box the points represent the allowed J values of the transitions. The values of J_ℓ are reported in ascending order on the horizontal axis, the values of J_u are reported in ascending order on the vertical axis. Note that the highest values are found for transitions with $\Delta L = 0, 1$ (diagonal and upper-diagonal boxes), and $\Delta J = \Delta L$. This second property holds particularly for high L -values.

where $H_u = B_t/B_c$, with B_t the microturbulent magnetic field intensity, and B_c the critical field intensity, defined (in Gauss) as

$$B_c = \frac{A}{0.879g_u}, \quad (8)$$

where A is the Einstein coefficient for spontaneous emission, expressed in 10^7 s^{-1} , and g_u the Landé factor of the upper level⁵. The critical field represents therefore the magnetic field needed to decrease the polarization by about a factor 2. Note that the critical field depends on the value of the Einstein coefficient, which in some cases is not known with high precision. Note also that two of the lines here considered (Ti I at 4536.054 Å, and Cr I at 3883.639 Å) have the Landé factor of the upper level equal to 0, and therefore are not sensitive to the magnetic field. If we assume that a microturbulent magnetic field is present in the quiet sun, we expect that the observed polarization should be stronger in those lines having a larger critical field. In Fig. 5 panels d–f the critical field intensity is represented through a color scale. The expected correlation between the polarization degree and the critical field intensity is suggested, although many “exceptions” are present. The role of the magnetic field is obviously important. However, it does not seem to be able to fully explain

the discrepancy previously discussed. Setting the anisotropy factor equal to 0.015 (for all the lines), the best fit between the observed values of Q/I and the values obtained through Eq. (7) is achieved for a microturbulent magnetic field on the order of 20 Gauss or larger (basically when most of the lines have reached the saturation regime). It is important to stress that this is nothing else than an exercise that can give some indications about the order of magnitude of the physical quantity under investigation. It would be naive to rely too much on the particular numerical value obtained, or even to give it a real physical meaning without keeping in mind the approximations that have been previously introduced. For a reliable inference of the strength of the magnetic field it is important to take into account the effects of radiative transfer and collisions in realistic models of the solar atmosphere, as shown by Trujillo Bueno et al. (2004) for the Sr I line at 4607 Å. Taking into account the effects of radiative transfer, and collisions for a large sample of lines is however much more difficult, also because our knowledge of the collisional rates is still very limited.

We conclude our discussion with two more plots based on Eq. (6). If we divide the observed value of Q/I of each signal by the corresponding $\mathcal{W}_2$, we should obtain something proportional to the anisotropy factor of the radiation field at the height of formation, and at the wavelength position of the various spectral lines. The anisotropy factor of the continuum has been plotted as a function of wavelength by

⁵ For the elements or ions showing hyperfine structure (HFS), the value of the Landé factor appearing in Eq. (8) is the one that would compete to the level neglecting HFS.

Manso Sainz & Landi Degl'Innocenti (2002), and it can be observed that in the wavelength range considered here, it decreases with wavelength approximately by a factor 2. If we plot the quantity $R = (Q/I)/W_2$ as a function of wavelength, we see that the points spread over the Cartesian plane, showing a slight decreasing trend with wavelength (see Fig. 5, panel e). The black dashed line, which represents the best linear fit to the points, shows more clearly the expected trend.

Since the observations of Gandorfer (Gandorfer 2000, 2002, 2005) were taken inside the limb, very likely the most relevant dependence that has to be considered is the variation of the anisotropy factor as a function of the height of formation of the various lines. In this sense it is therefore interesting to plot the quantity R as a function of the reduced equivalent width, since, as a first approximation, lines with similar equivalent widths should form at similar heights. Note that the application of Eq. (6) for the investigation of this kind of dependence is not fully consistent, as it is correct only for tangential observations, and it is based upon the assumption that the illuminating radiation field should be the same for the various components of the multiplet. As can be observed from panel f of Fig. 5, in this case the points spread over the Cartesian plane, without showing any particular trend. As far as the sensitivity to a microturbulent magnetic field is concerned, we observe that, as expected, lines with larger critical fields are in general more polarized, but too many exceptions are present in order to draw any conclusion. On the contrary, these results stress the fact that the mechanism through which the polarization is produced, and modified, is extremely complex. In particular, there are many physical processes that are involved in the generation and modification of the polarization (see, for example, Shchukina & Trujillo Bueno 2008). As previously observed, for some of these processes we do not have a reliable knowledge of all the physical parameters which are needed in order to quantify their effects.

6. Conclusions

We have carried out a detailed analysis of the second solar spectrum, as plotted in graphical form in the three volumes of the atlas “The Second Solar Spectrum” (Gandorfer 2000, 2002, 2005). All the strongest polarization signals due to atomic transitions have been identified, classified according to the shape of their Q/I profile, and listed together with the most relevant spectroscopic properties of the corresponding lines. From the analysis of these data, three empirical rules have been formulated. The rules concern the properties of the lower level, a correlation between the shape of the polarization profiles and the reduced equivalent width of the lines in the intensity spectrum, and the quantum numbers involved in the transitions. Our initial purpose to investigate the possible existence of common properties among the strongest polarization signals of the second solar spectrum has therefore been met with success. These three rules might represent the first step to understand why only particular spectral lines show at the limb strong polarization signals, which is one of the most interesting open questions concerning the second solar spectrum.

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Table 1. Table of the most polarizing atomic spectral lines of the second solar spectrum (3160 Å–6995 Å). The lines are listed by increasing wavelength. The various quantities that are listed for each line are described in Sect. 2.3.

#	λ^{Sun} (Å)	Elem.	W_{λ} (mÅ)	W_{λ}/λ (F)	$(Q/I)^{\text{M}}$ (%)	$(Q/I)^{\text{m}}$ (%)	Q/I (%)	Type	Notes
Volume III									
1	3179.342	Ca II	580	182	0.85	0.50	0.35	W	¹
2	3217.935	Ti I	35	11.1	0.75	0.60*	0.15	S*	²
3	3230.592	Sm II	34	10.5	0.86	0.65*	0.21	S*	³
4	3234.518	Ti II	49	15.2	0.62	0.50	0.12	M1	⁴
					1.35	0.85	0.50		
5	3242.007	Ti II	270	83.0	0.95	0.80	0.15	M1	
					1.07	0.84	0.23		
6	3247.569	Cu I	246	76.0	1.75	0.82	0.93	M0	⁵
7	3248.612	/Ti II Ti I	148	46.0	0.57	0.40	0.17	W	⁶
8	3260.552	Nb II	20	6.1	0.85	0.70*	0.15	S	
9	3273.052	Zr II	78	23.9	0.77	0.58	0.19	W	
10	3273.972	Cu I	221*	67.4	0.36	0.19	0.17	W	⁷
11	3308.399	Ti I	32	9.7	0.92	0.58*	0.34	S	
12	3322.949	Ti II (Zr II)	495*	157.3	0.42	0.27	0.15	M1	⁸
					0.75	0.64	0.11		
13	3326.777	//Ti II–Zr II	214	64.0	0.275	0.175	0.100	W	
14	3372.812	Ti II	459	135.9	0.67	0.55	0.12	M0	
15	3380.260	Ti II	30	31.2	0.25	0.15	0.10	W	⁹
16	3380.585	Ni I	809	239	0.275	0.175	0.100	W	⁹
17	3383.765	Ti II	430*	127	0.65	0.53	0.12	M0	
18	3391.973	Zr II	113*	20.0	0.42	0.32	0.10	W	
19	3405.126	Co I	206	60.5	0.67	0.49	0.18	M0	
20	3407.805	Dy II	60	18.8	0.42	0.32*	0.10	S*	
21	3433.579	//Ni I–Cr I	492	143	0.25	0.15	0.10	W	
22	3439.229	Gd II	10	3.5	0.53	0.40*	0.13	S	
23	3446.271	Ni I	470	136	0.335	0.235	0.100	M1	¹⁰
					0.575	0.435	0.14		
24	3452.905	Ni I	247	73.1	0.41	0.22	0.19	W	
25	3453.512	Co I	310	87.9	0.36	0.24	0.12	W	¹¹

¹ The linear polarization signal is quite noisy at this wavelength, and it is not possible to measure the amplitude of the Q/I profile with high precision. There are four more lines in this spectral region that, although showing linear polarization peaks with amplitudes apparently larger than 0.1%, have not been included in this table because of the high noise level: Fe I at 3171.665 Å, //Fe I at 3172.051 Å, Cr II Fe I p (CH) at 3172.087 Å, and Fe I at 3180.236 Å.

² The polarization peak does not fall exactly at line center. This could be due to the fact that the line is severely blended with a depolarizing Ni I line at 3217.841 Å, which may imply also a reduction of the peak amplitude.

³ This signal is a typical case where it is not easy to establish the reference level from which the amplitude of the Q/I peak has to be measured.

⁴ This signal has been associated with the Ti II line since the Q/I central peak falls at the wavelength position of the line-core of this spectral line, and because it is very similar to the signal produced by the Ti II line at 3242.007 Å, which belongs to the same multiplet. However, the strong polarization signal in the wings may be produced by the combined action of this line and of the nearby line at 3234.647 Å (Ni I–Fe I).

⁵ This is a very deep line in the intensity spectrum, and unavoidably the polarization signal is rather noisy at line center. For this reason it is not easy to determine if it has to be classified as “M0” or “M1”. The polarization lobe in the blue wing of the line is almost completely destroyed by the presence of depolarizing blended lines.

⁶ The “W” shape of this signal might be due to the effect of depolarizing lines blended with the red and blue wings of this spectral line.

⁷ The polarization peak does not fall exactly at line center. This displacement, as well as the large width of the intensity profile of this line, could be explained by the presence of a blend with an OH line, or in terms of the hyperfine structure shown by this element.

⁸ The depolarization observed beside the line-core peak of this line might be affected by the presence of blended lines. Moreover, it is not possible to exclude that the polarization observed in the far wings could be affected (or due) to the NH band. In this latter case the signal should be classified as “W”.

⁹ These lines are severely blended. The larger reduced equivalent width of the Ni I line suggests that the broad depolarization is due to this line, while the Ti II line produces a much narrower “W” signal.

¹⁰ The polarization peak at line center shows a substructure made of two secondary peaks separated by a small dip.

¹¹ It is not possible to exclude that this signal might be of type “M1”, the wing-peaks being hidden by blended lines.

Table 1. continued.

#	λ^{Sun} (Å)	Elem.	W_{λ} (mÅ)	W_{λ}/λ (F)	$(Q/I)^{\text{M}}$ (%)	$(Q/I)^{\text{m}}$ (%)	Q/I (%)	Type	Notes
26	3458.467	Ni I	656	189	0.28 <i>0.60</i>	0.14 <i>0.42</i>	0.14 <i>0.18</i>	M1	
27	3461.667	Ni I	758	219	0.33	0.16	0.17	W	¹⁰
28	3464.474	Sr II (Fe II)	63	18.2	0.44	0.32*	0.12	S	
29	3465.766	Co I	69	84.2	0.240	0.125	0.115	W	¹²
30	3465.880	Fe I	544	158	0.26	0.15	0.11	W	¹²
31	3469.493	Ni I (V II)	180	52.2	0.27	0.15	0.12	W	
32	3472.558	Ni I	374	136	0.31	0.175	0.135	W	
33	3476.712	Fe I	465	136	0.34	0.19	0.15	W	
34	3485.110	Ni I	100	29.2	0.33	0.23*	0.10	S*	
35	3492.975	Ni I	826	239	0.25	0.15	0.10	W	
36	3494.515	/Cr II Dy II	46	13.2	0.375	0.26*	0.115	S*	¹³
37	3504.892	Fe I /Ti II	132	37.6	0.36	0.22	0.14	W	
38	3510.846	Ti II	87	29.1	0.40	0.28*	0.12	S	
39	3515.066	Ni I	718	202	0.22	0.10	0.12	W	
40	3519.618	Zr I	7.5	2.6	0.36	0.23*	0.13	S	
41	3521.270	Fe I	381	110	0.24	0.11	0.13	W	
42	3533.014	Fe I	97	31.4	0.35	0.20	0.15	W	¹⁴
43	3550.222	–Dy II	43	12.0	0.42	0.31	0.11	S	¹⁵
44	3553.095	Pd I	48*	3.4	0.385	0.20*	0.185	S	¹⁶
45	3554.937	Fe I	404	111	0.21	0.11	0.10	W	
46	3556.597	Zr II	23	7.0	0.32	0.18*	0.14	S	
47	3558.532	/Fe I–Sc II	485	137	0.23	0.05	0.18	W	
48	3565.396	Fe I	990	274	0.20	0.08	0.12	W	¹⁷
49	3566.383	Ni I	458	141	0.32 <i>0.38</i>	0.22 <i>0.30</i>	0.10 <i>0.08</i>	M1	¹⁷
50	3570.134	Fe I	1380	387	0.34 <i>0.41</i>	0.20 <i>0.29</i>	0.14 <i>0.12</i>	M1	
51	3578.693	Cr I	488	142	0.42 <i>0.435</i>	0.17 <i>0.285</i>	0.25 <i>0.150</i>	M1	
52	3581.209	Fe I	2144	599	0.34 <i>0.41</i>	0.18 <i>0.28</i>	0.16 <i>0.13</i>	M1	
53	3585.714	Fe I	168	63.0	0.22	0.11	0.11	W	¹⁸
54	3585.844	Co I?–Ti I	25	22.6	0.40	0.26*	0.14	S	¹⁸
55	3586.990	Fe I	532	147	0.22	0.09	0.13	W	
56	3589.222	Ru I	18	5.7	0.375	0.275	0.100	S	
57	3590.489	Sc II	136	37.9	0.21 <i>0.375</i>	0.05 <i>0.275</i>	0.16 <i>0.100</i>	M1	¹⁹

¹² These lines are severely blended, and it is difficult to understand if they are both “W”, or if only one is “W”, the other one being “S”.¹³ The polarization peak does not fall exactly at line center.¹⁴ This line falls in the blue depolarizing wing of a Fe I line, and it is not easy to determine if this signal has to be classified as “S” or “W”.¹⁵ The polarization peak has quite a large width. This could be due to the unidentified blended line, or to the hyperfine structure shown by this element. This second hypothesis is supported by the similarity with the polarization signal of the Dy II line at 3407.805 Å.¹⁶ It is not easy to establish the reference level from which the amplitude of the Q/I peak has to be measured.¹⁷ It is not possible to exclude that the polarization peak at 3566.7 Å could be due to the interferences between the Fe I lines at 3565.396 Å and 3570.134 Å, which belong to the same multiplet. In this case the Fe I signal should be classified as “M1” instead of “W”, while the Ni I signal as “W” instead of “M1”.¹⁸ The width of the polarization peak at the wavelength position of the Co I–Ti I line (line # 54) is a little surprising. It is not possible to exclude that this peak might pertain to a possible “M1” structure of the Fe I line at 3585.714 Å. In this case, the Co I–Ti I line should be excluded.¹⁹ In the blue wing of this line the polarization might be enhanced by (or due to) the presence of a blending Fe I line at 3590.302 Å, in the red wing it could be affected by the wing-lobe of the far, strong Cr I line at 3593.495 Å. It is difficult, therefore, to determine if this line should be classified as “M1”, or “W”.

Table 1. continued.

#	λ^{Sun} (Å)	Elem.	W_{λ} (mÅ)	W_{λ}/λ (F)	$(Q/I)^{\text{M}}$ (%)	$(Q/I)^{\text{m}}$ (%)	Q/I (%)	Type	Notes
58	3592.027	V II	75	21.0	0.20	0.10	0.10	W	
59	3593.495	Cr I	436	127	0.775 0.95	0.270 0.27	0.505 0.68	M1	
60	3594.638	Fe I	146	40.8	0.30	0.17	0.13	W	
61	3594.876	Co I	92	25.7	0.25	0.14	0.11	W	
62	3596.054	Ti II	95	26.7	0.21	0.07	0.14	W	²⁰
63	3597.712	Ni I	181	50.2	0.29 0.36	0.12 0.27	0.17 0.09	M1	²¹
64	3600.739	Y II	69	19.2	0.35	0.25	0.10	W	²²
65	3601.198	Zr I	13	3.6	0.42	0.31*	0.11	S	
66	3602.287	Ni I	94	26.2	0.18	0.06	0.12	W	
67	3605.339	//Cr I Co I	495	136	0.24	0.09	0.15	W	
68	3608.869	Fe I	1046	287	0.31 0.44	0.18 0.26	0.13 0.18	M1	
69	3610.166	//Fe I Ti I	231	65.4	0.26	0.11	0.15	W	
70	3610.460	Ni I	250*	52.0	0.27	0.08	0.19	W	
71	3618.777	Fe I	1410	385	0.39 0.35	0.15 0.25	0.24 0.10	M1	²³
72	3619.400	Ni I	568	204	0.30	0.16	0.14	W	
73	3621.467	Fe I	140	40.6	0.19	0.09	0.10	W	
74	3624.733	Ni I	132	37.1	0.165	0.04	0.125	W	
75	3631.475	//Fe I Cr II	1364	369	0.21 0.31	0.11 0.24	0.10 0.07	M1	
76	3633.138	Y II	134*	19.0	0.51	0.24	0.27	S	
77	3647.851	Fe I (Fe I)	970	313	0.28 0.31	0.11 0.23	0.17 0.08	M1	
78	3651.800	Sc II	114	39.1	0.14	0.04	0.10	W	
79	3664.097	Ni I	130	43.8	0.19	0.08	0.11	W	
80	3674.150	Ni I	178*	33.0	0.16	0.06	0.10	W	
81	3694.817	Dy II	24	9.2	0.30	0.20*	0.10	S	
82	3705.577	Fe I	562	180	0.15	0.05	0.10	W	
83	3710.292	Y II	74	27.2	0.40	0.25*	0.15	S	
84	3719.947	Fe I	1664	538	0.34	0.24	0.10	M0	²⁴
85	3724.574	Ti I	60	23.1	0.475	0.320	0.155	S	
86	3728.042	Ru I	40	20.0	0.30	0.20*	0.10	S*	²⁵
87	3733.841	Cr I?	2	2.3	0.57	0.42	0.15	S	²⁶
88	3734.874	Fe I	3027	945	0.480	0.275	0.205	W	²⁷
89	3737.141	Fe I	1071	428	0.31	0.16	0.15	W	
90	3741.312	Sm II–Eu II	13	5.0	0.57	0.38*	0.19	S	²⁸
91	3742.278	Ru I	6	2.4	0.50	0.375*	0.125	S	

²⁰ Very likely the polarization in the blue wing is due to the strong Cr I line at 3593.495 Å, while in the red wing to the Ni I line at 3597.712 Å. If this is not the case, the signal should be classified as “M1”.

²¹ It is not possible to exclude that the polarization in the far wings of this line might be the wing-lobes of the far Cr I line at 3593.495 Å. In this case the signal should be classified as “W”.

²² The polarization lobes in the far wings do not seem to be due to this line. If this is not the case, the signal should be classified as “M1”.

²³ We have classified this signal as “M1”, since its wing-lobes appear to be severely blended by several depolarizing lines.

²⁴ This line produces a very broad polarization signal. The amplitude of the wing-lobes has been measured in the blue wing at 3717.0 Å.

²⁵ The polarization peak does not fall exactly at line center, being slightly shifted to the blue.

²⁶ This polarization signal, though being located at the wavelength position corresponding to a (possible) Cr I line, might be due either to CN or to the strong, nearby Fe I line at 3734.874 Å.

²⁷ It is not possible to exclude that the signal at 3733.841 Å (# 87) might be due to this Fe I line. In this case this signal should be classified as “M1” instead of “W”.

²⁸ The polarization peak does not fall exactly at line center, being slightly shifted to the blue. This may indicate that the signal is due to Sm II.

Table 1. continued.

#	λ^{Sun} (Å)	Elem.	W_{λ} (mÅ)	W_{λ}/λ (F)	$(Q/I)^{\text{M}}$ (%)	$(Q/I)^{\text{m}}$ (%)	Q/I (%)	Type	Notes
92	3743.368	Fe I	592	193	0.275	0.175	0.100	W	
93	3745.574	Fe I	1202*	459	0.325	0.200	0.125	W	
94	3745.910	Fe I (Zr II)	540	301	0.575	0.280*	0.295	S	29
95	3748.271	Fe I	497	228	0.32	0.18	0.14	W	
96	3748.966	/Fe I Cr I	103	82.9	0.275	0.175	0.100	W	
97	3749.495	Fe I	1907	578	0.45	0.20	0.25	W	
98	3753.620	/Fe I–Ti I	132	45.0	0.16	0.30	0.14	W	30
99	3758.245	Fe I	1647	497	0.40 0.69	0.22 0.42	0.18 0.27	M1	
100	3759.299	Ti II	334	115	0.41	0.31	0.10	W	31
101	3761.320	Ti II	277*	61.0	0.48 0.70	0.38 0.41	0.10 0.29	M1	
102	3763.803	Fe I	829	255	0.36 0.72	0.15 0.40	0.21 0.32	M1	32
103	3767.204	Fe I	820	262	0.28 0.55	0.18 0.40	0.10 0.15	M1	
104	3780.516	/CN–Zr I	26	9.5	0.51	0.39	0.12	S	33
105	3782.318	CN /Y II	18	6.3	0.485	0.385	0.100	S	
106	3784.252	Nd II–Fe I p	16	5.8	0.65	0.38	0.27	S	34
107	3787.236	V II CN	139*	17.2	0.50	0.38	0.12	S	
108	3788.861	/Cr I–CN	69*	17.4	0.59	0.38	0.21	S	
109	3791.194	CN Nb I	8.5	3.2	0.50	0.38	0.12	S	
110	3792.565	/CN Y II	33	15.0	0.67	0.38	0.29	S	
111	3796.974	CN Cr I	20	16.1	0.540	0.375	0.165	S	
112	3801.371	Fe I–CN	75	30.2	0.550	0.375	0.175	S	
113	3801.542	Ce II CN	50	21.0	0.575	0.375	0.200	S	
114	3806.375	CN Fe I	67	22.0	0.63	0.37	0.26	S	
115	3807.937	/Cr I–CN	111	35.2	0.52	0.39*	0.13	S	35
116	3809.162	Fe I	24	9.5	0.62	0.37	0.25	S	36
117	3811.380	CN Ti I?	35	16.0	0.64	0.37	0.27	S	
118	3812.199	CN Y II	44*	4.5	0.51	0.37	0.14	S	
119	3813.491	V I	54	28.4	0.49	0.36	0.13	S	37
120	3814.892	CN Ti I	26	15.7	0.58	0.36	0.22	S	
121	3817.843	V I CN Cr I	40	16.0	0.50	0.36	0.14	S	
122	3824.750	CN Fe I p	11	10.5	0.31	0.20*	0.11	S*	
123	3826.770	CN–V I Ni I	15	11.2	0.48	0.35	0.13	S	
124	3826.957	CN–/V II	32	21.7	0.47	0.35	0.12	S	

²⁹ This signal falls in the depolarizing wing of the broad Fe I line at 3745.574 Å (belonging to the same multiplet), and it is difficult to determine if this is a “S” or a “W” signal.

³⁰ The dip in the red wing, which is free of blends, induces to believe that this is a “W” signal, the dip in the blue wing being missing because of the blend with the Dy II–CN line at 3753.525 Å.

³¹ This signal falls in the strongly polarized red wing of the Fe I line at 3758.245 Å, and it is not possible to exclude that it might be classified as an “M” signal. Note that the Ti II line at 3761.320 Å (classified as “M1”) belongs to the same multiplet.

³² The amplitude of the wing-lobe might be enhanced by the presence of CN lines.

³³ The polarization peak does not fall exactly at line center, but it is slightly shifted to the blue. This may be an indication that the signal is due to CN.

³⁴ Given the extremely low value of the Einstein coefficient of the Fe I line ($2 \times 10^3 \text{ s}^{-1}$), it seems quite reasonable to believe that this signal is produced by the Nd II line.

³⁵ The polarization peak does not fall exactly at line center, but it is slightly red-shifted. This is a strong hint that this signal might be due to CN.

³⁶ The polarization peak does not seem to be as sharp as for an isolated line. Probably there is a contribution coming from the CN molecule.

³⁷ The width of this polarization signal suggests that it might be enhanced by (or due to) the strongly blending Ti II line at 3813.394 Å. It is not possible to exclude therefore that the Ti II line should be included in the table, and classified as “M0”.

Table 1. continued.

#	λ^{Sun} (Å)	Elem.	W_{λ} (mÅ)	W_{λ}/λ (F)	$(Q/I)^{\text{M}}$ (%)	$(Q/I)^{\text{m}}$ (%)	Q/I (%)	Type	Notes
125	3829.365	Mg I	874	308	0.50	0.26	0.24	M1	³⁸
126	3830.311	CN? Sm II	7.5	3.8	0.49	0.35	0.14	S	³⁹
127	3832.310	Mg I	1685	600	0.225	0.10	0.125	M1	³⁸
128	3838.302	Mg I	1920	641	0.27	0.16	0.11	M1	³⁸
129	3846.986	CN–Zr I	110*	9.6	0.435	0.335	0.10	S	
130	3848.611	CN Ce II	41	13.5	0.470	0.335	0.135	S	⁴⁰
131	3851.172	V I CN	24	9.6	0.50	0.335	0.165	S	
132	3851.599	CN Fe I	13	6.1	0.565	0.330	0.235	S	
133	3867.863	CN Ru I	100*	1.6	0.500	0.325	0.175	S	
134	3869.313	Ti I–CN	120*	22.5	0.475	0.320	0.155	S	
135	3870.552	CN Co I	74*	19.4	0.435	0.320	0.115	S	
136	3871.136	CN V I?	13	18.8	0.45	0.32	0.13	S	
137	3872.179	CN Fe I?	19	12.4	0.525	0.320	0.205	S	⁴⁰
138	3883.639	Cr I	26	9.3	0.67	0.44*	0.23	S	
139	3891.781	Ba II	30	11.6	0.54	0.40*	0.14	S	
Volume II									⁴¹
140	3920.269	Fe I	341	101	0.50	0.15	0.35	W	
141	3922.923	Fe I	414	124	0.72	0.20	0.52	W	⁴²
142	3927.933	Fe I (CH)	187	144	0.51	0.10	0.41	W	
143	3933.682	Ca II [K]	20 253	4874	0.80	0.00	0.80	M1	⁴³
144	3987.966	Yb I	18	5.0	0.53	0.42*	0.11	S	
145	4030.763	Mn I	326*	75.2	0.28	0.05	0.23	W	⁴⁴
146	4033.072	Mn I	229*	54.8	0.16	0.05	0.11	W	⁴⁴
147	4034.492	Mn I	213*	46.1	0.27	0.10	0.17	W	
148	4039.096	Cr I	42	10.4	0.445	0.345	0.100	S	
149	4040.790	Ce II–Nd II	39	9.6	0.48	0.345	0.135	S	⁴⁵
150	4045.825	Fe I	1174	316	0.465 0.73	0.190 0.34	0.275 0.39	M1	
151	4049.862	Gd II /Fe I	11	2.7	0.67	0.44*	0.23	S	
152	4062.232	Ce II	6	1.5	0.49	0.33	0.16	S	
153	4063.605	Fe I (Mn I)	787	219	0.34 0.50	0.08 0.33	0.26 0.17	M1	

³⁸ The wing-lobes of these lines are probably heavily affected (enhanced) by several CN lines. For this reason the wing-lobe amplitudes have not been measured.³⁹ The polarization signal is severely blended with other CN lines.⁴⁰ The polarization peak does not fall exactly at line center, but is somewhat red-shifted.⁴¹ Volume III of the atlas covers the spectral interval between 3160 Å and 3915 Å, Vol. II the spectral interval between 3910 Å and 4630 Å. The spectral interval between 3910.0 Å and 3913.5 Å is covered by both volumes. Comparing the observations made in this spectral interval, it can be noticed that the theoretical continuum plotted in Vol. III is slightly lower than in Vol. II, while the peaks observed in Q/I in Vol. III are slightly larger than in Vol. II. This might be due to the fact that, although the nominal position of the slit is $\mu = 0.1$ for the observations of both atlases, because of the seeing the “effective” position might be different from the nominal value.⁴² At line center this signal shows quite a complex profile, with several secondary peaks and dips.⁴³ At line center the Ca II K line shows a “M” type profile, but it is important to note that quantum interferences between the Ca II H and K lines produce a much broader signal that starts in the far blue wing of the K line, at about 3890 Å, with a positive lobe. The polarization becomes negative between the K and H lines, and it is zero (without showing any particular structure) at the wavelength position of the H line. This structure (which does not enter the classification scheme proposed in this work) has already been explained in terms of quantum interferences by [Stenflo \(1980\)](#) and [Landi Degl’Innocenti & Landolfi \(2004\)](#). It is quite surprising, however, that the atlas does not show any positive lobe in the red wing of the Ca II H line, predicted on the other hand by the theory. This might be due to the choice of the level of the local polarized continuum, which may be wrong between 3972 Å and 3990 Å. Note that where the polarization is negative, a depolarizing line produces a Q/I peak. For this reason, all the lines producing polarization peaks in this spectral interval have not been included in the table. Note also that three lines (Sc I, V I and Co I), falling within an interval of ≈ 0.5 Å centered at the core of the Ca II K line, are listed as masked lines by [Moore et al. \(1966\)](#).⁴⁴ At line center this signal shows quite a complex profile with several secondary peaks and dips, perhaps due to hyperfine structure.⁴⁵ The polarization signal is slightly blue-shifted with respect to line center.

Table 1. continued.

#	λ^{Sun} (Å)	Elem.	W_{λ} (mÅ)	W_{λ}/λ (F)	$(Q/I)^{\text{M}}$ (%)	$(Q/I)^{\text{m}}$ (%)	Q/I (%)	Type	Notes
154	4071.749	Fe I	723	191	0.41 <i>0.63</i>	0.16 <i>0.32</i>	0.25 <i>0.31</i>	M1	⁴⁶
155	4077.724	Sr II	428*	100	1.225 <i>1.10</i>	0.320 <i>0.32</i>	0.905 <i>0.78</i>	MS	
156	4083.226	Ce II	26	6.4	0.47	0.32	0.15	S	
157	4109.450	Nd II	39	9.5	0.42	0.30	0.12	S	
158	4115.376	Ce II	11	2.7	0.430	0.295	0.135	S	
159	4128.309	Y I	12	2.9	0.595	0.290	0.305	S	
160	4129.724	Eu II	54	12.1	0.465	0.285	0.180	S	
161	4130.657	Ba II	45	10.9	0.53	0.26*	0.27	S	⁴⁷
162	4142.842	Y I	22	5.3	0.445	0.280	0.165	S	
163	4186.126	Ti I	42	10.0	0.53	0.27*	0.26	S	
164	4222.602	Ce II	22	5.2	0.42	0.30*	0.12	S	
165	4226.740	Ca I	1476	342	2.190 <i>2.700</i>	0.235 <i>0.235</i>	1.955 <i>2.465</i>	M1	
166	4233.612	Fe I	298	70.4	0.14	0.24	0.10	W	⁴⁸
167	4235.949	Fe I (Cr I) (Y I)	385	90.9	0.12	0.27	0.15	W	⁴⁹
168	4237.891	Ti I	16	4.0	0.38	0.23	0.15	S	
169	4246.837	Sc II	171	40.3	0.460 <i>0.470</i>	0.225 <i>0.225</i>	0.235 <i>0.245</i>	MS	⁵⁰
170	4250.130	Fe I	342*	79.5	0.26	0.12	0.14	W	
171	4254.346	Cr I (V II)	393	92.4	0.40 <i>0.270</i>	0.16 <i>0.225</i>	0.24 <i>0.045</i>	M1	
172	4268.628	V I	23	5.6	0.45	0.22	0.23	S	
173	4271.774	Fe I	756	177	0.24	0.09	0.15	W	
174	4274.806	Cr I	196	45.8	0.59 <i>0.36</i>	0.22 <i>0.22</i>	0.37 <i>0.14</i>	M1	
175	4283.014	Ca I	133	31.0	0.33	0.18	0.15	W	⁵¹
176	4289.922	Fe I (Ce II)	65	19.1	0.285	0.170	0.115	S	
177	4299.249	/Fe I Ti I (CH)	212	49.3	0.22	0.12	0.10	W	⁵²
178	4307.748	Ca I	59	40.2	0.14	0.04	0.10	S	⁵³
179	4307.912	/Fe I Ti II (CH)	723	165	0.14	0.04	0.10	W	⁵⁴
180	4325.775	Fe I (Fe I p)	793	174	0.32 <i>0.380</i>	0.12 <i>0.195</i>	0.20 <i>0.185</i>	M1	
181	4339.722	Cr I	69	23.8	0.27	0.15*	0.12	S	
182	4340.475	H I [H _{γ}]	2855	659	0.25	0.13	0.12	W	
183	4354.436	La II	13	3.4	0.295	0.195*	0.100	S	⁵⁵
184	4374.944	Y II	88	20.1	0.39	0.18	0.21	S	

⁴⁶ At line center this signal shows quite a complex profile with several secondary peaks and dips.⁴⁷ This line is severely blended with a weaker Ce II line. In the absence of this blend, the amplitude of Q/I peak might be different.⁴⁸ At line center this signal shows quite a complex profile with several secondary peaks and dips.⁴⁹ It is not possible to exclude that the “W” shape of this signal could be due to the depolarization produced by several blending lines.⁵⁰ The polarization profile shows a complex structure (that might be due to hyperfine structure), and an extended blue wing.⁵¹ The depolarization in the blue wing of this profile is rather peculiar. For this reason the reference level for measuring the signal amplitude has been taken in the dip of the red wing.⁵² It is difficult to measure the amplitude of this signal because of the presence of several blends.⁵³ It is difficult to decide whether this line has to be classified as “S” or “W” because of the blend with the /Fe I Ti I (CH) line at 4307.912 Å, and because the polarization signal is quite noisy around this wavelength.⁵⁴ At line center this line shows a two-peak structure, probably due to the blend.⁵⁵ The polarization peak does not fall exactly at line center, probably because of the presence of a strong blend with a Mg I line. It is not possible to exclude that in the absence of this blend, the Q/I peak amplitude would have been significantly larger.

Table 1. continued.

#	λ^{Sun} (Å)	Elem.	W_{λ} (mÅ)	W_{λ}/λ (F)	$(Q/I)^{\text{M}}$ (%)	$(Q/I)^{\text{m}}$ (%)	Q/I (%)	Type	Notes
185	4383.557	Fe I	1008	235	0.410 <i>0.305</i>	0.110 <i>0.175</i>	0.300 <i>0.130</i>	M1	⁵⁶
186	4404.761	Fe I	898	181	0.29 <i>0.23</i>	0.06 <i>0.17</i>	0.23 <i>0.06</i>	M1	
187	4415.135	Fe I	417*	92.9	0.07	0.20	0.13	W	
188	4425.444	Ca I	145	31.6	0.275	0.165	0.110	S	
189	4431.292	Ti I	5	1.1	0.38	0.16	0.22	S	⁵⁷
190	4453.710	Ti I	36	9.0	0.280	0.155	0.125	S	
191	4460.225	Ce II	100*	6.0	0.315	0.155	0.160	S	⁵⁸
192	4462.993	Nd II	13	2.9	0.26	0.15	0.11	S	
193	4471.244	Ti I (Ce II)	35	8.5	0.265	0.165*	0.100	S	
194	4486.914	Ce II	11	2.5	0.28	0.15	0.13	S	
195	4500.288	Cr I	39*	6.2	0.230	0.145	0.085	S	
196	4511.900	Cr I	31	8.4	0.180	0.125*	0.055	S	
197	4527.325	//Ti I /Cr I (Ce II)	67	14.8	0.210	0.140	0.070	S	
198	4536.054	Ti I	147*	16.3	0.240	0.125*	0.115	S	
199	4540.710	Cr I	52	12.3	0.165	0.110*	0.055	S	
200	4554.036	Ba II	159	36.7	0.78 <i>0.50</i>	0.13 <i>0.13</i>	0.65 <i>0.37</i>	MS	
201	4572.284	Ce II	15	3.3	0.205	0.130	0.075	S	
202	4595.593	Cr I	21	4.6	0.255	0.105*	0.150	S	
203	4599.227	Ti I	6	1.3	0.185	0.120	0.065	S	
204	4607.338	Sr I	36	7.8	1.200	0.120	1.080	S	
Volume I									⁵⁹
205	4639.368	Ti I	36	8.4	0.185	0.115	0.070	S	
206	4639.946	Ti I	31	7.3	0.175	0.115	0.060	S	
207	4679.983	Fe I p	6.5	1.4	0.155	0.105	0.050	S	
208	4703.003	Mg I	326	71.9	0.095	0.045	0.050	W	
209	4742.798	Ti I	27	5.7	0.290	0.098	0.192	S	
210	4758.124	Ti I	40	8.2	0.202	0.095	0.107	S	
211	4759.276	Ti I	41	8.6	0.192	0.095	0.097	S	
212	4778.258	Ti I	16	3.3	0.148	0.092	0.056	S	
213	4796.189	Cr I—//Ti I	24	5.0	0.145	0.090	0.055	S	
214	4799.794	V I—//Ti I	75*	10.2	0.175	0.089	0.086	S	
215	4805.420	Ti I	37	7.7	0.150	0.087	0.063	S	
216	4840.884	Ti I	60	12.6	0.136	0.082	0.054	S	⁶⁰
217	4868.263	Ti I	26	5.5	0.130	0.080	0.050	S	
218	4975.351	Ti I	35*	3.6	0.165	0.070	0.095	S	⁶¹
219	5021.923	Cr I Fe I C2	22	4.4	0.115	0.065	0.050	S	
220	5025.764	Fe I C2	11	2.2	0.124	0.063	0.061	S	
221	5112.279	Zr II	8	1.6	0.106	0.056	0.050	S	

⁵⁶ At line center this line shows a complex structure, with several secondary peaks and dips.⁵⁷ This line is severely blended with a Sc II line. In the absence of this blend the amplitude of the Q/I signal might be larger.⁵⁸ This line is severely blended with a V I line. In the absence of this blend the amplitude of the Q/I signal might be larger.⁵⁹ Volume II of the atlas covers the spectral interval between 3910 Å and 4630 Å, Vol. I the spectral interval between 4625 Å and 6995 Å. The spectral interval between 4624 Å and 4626.5 Å is covered by both volumes. Comparing the observations made in this spectral interval, it can be noticed that the depolarization produced by two rather intense lines (Fe I and Cr I) is larger in Vol. I than in Vol. II. As already discussed in the note 41, this might be due to the fact that, although the nominal position of the slit is $\mu = 0.1$ for the observations of both atlases, because of the seeing the “effective” position might be different from the nominal value.⁶⁰ A secondary peak is observed to the blue of line center. The observation in this spectral region is quite noisy, and at this level it is not possible to exclude that the signal could be of “W” type.⁶¹ This line is severely blended with a Fe I line. In the absence of this blend the amplitude of the Q/I signal might be larger.

Table 1. continued.

#	λ^{Sun} (Å)	Elem.	W_{λ} (mÅ)	W_{λ}/λ (F)	$(Q/I)^{\text{M}}$ (%)	$(Q/I)^{\text{m}}$ (%)	Q/I (%)	Type	Notes
222	5113.127	/Cr I MgH	23	4.5	0.120	0.056	0.064	S	
223	5115.790	Fe I	23	4.5	0.120	0.056	0.064	S	⁶²
224	5120.420	Ti I	31	6.0	0.135	0.055	0.080	S	⁶³
225	5138.717	Cr I–MgH	13	2.4	0.130	0.055	0.075	S	
226	5139.648	Cr I	46	8.9	0.120	0.054	0.066	S	⁶⁴
227	5146.119	Fe II p C2	37	6.6	0.140	0.054	0.086	S	⁶⁵
228	5149.796	Co I MgH	11	2.1	0.126	0.053	0.073	S	
229	5153.241	Cu I	56*	8.5	0.163	0.053	0.110	S	⁶⁶
230	5167.327	Mg I	935*	173	0.130	0.030	0.100	W	
231	5171.028	Ru I MgH	5	1.0	0.110	0.052	0.058	S	
232	5176.792	/V I–MgH	10	1.9	0.115	0.051	0.064	S	
233	5196.452	Cr I	34	6.5	0.090	0.040*	0.050	S	⁶⁷
234	5206.044	Cr I (Ti I)	216*	36.6	0.115 0.115	0.050 0.050	0.065 0.065	MS	⁶⁸
235	5208.432	Cr I	247	47.4	0.110 0.077	0.040 0.050	0.070 0.027	MS	⁶⁸
236	5218.209	Cu I	48	9.8	0.101	0.049	0.052	S	
237	5239.823	Sc II	55	10.5	0.117	0.048	0.069	S	
238	5387.565	Cr I	25*	1.8	0.100	0.040	0.060	S	⁶⁹
239	5528.418	Mg I	293	53.8	0.052	0.000	0.052	W	
240	5535.51	Ba I	113*		0.165	0.032	0.133	S	
241	5565.485	Ti I	16	2.9	0.150	0.031	0.119	S	
242	5598.491	Ca I	118	21.1	0.080	0.030	0.050	S	
243	5644.146	Ti I	29	5.1	0.260	0.029	0.231	S	
244	5889.973	Na I [D ₂]	752*	120	0.330 0.220	0.021 0.021	0.309 0.199	MS	
245	5895.940	Na I [D ₁]	564*	91.0	0.05	−0.02	0.07	–	⁷⁰
246	6024.068	Fe I	117*	19.8	0.060	0.010*	0.050	S	
247	6141.727	/Ba II–Fe I	113	19.4	0.059	0.000	0.059	W	
248	6562.808	H I [H _{α}]	4020	649	0.120	0.010	0.110	S	⁷¹

⁶² This line has an extremely weak Einstein coefficient ($5.15 \times 10^4 \text{ s}^{-1}$), and it is not possible to exclude that this polarization signal might be due to a C₂ line.

⁶³ The polarization peak does not fall exactly at line center, probably because of the presence of a strong blend with a Fe II p C₂ line. It is not possible to exclude that in the absence of this blend, the Q/I peak amplitude would have been larger.

⁶⁴ This line is severely blended with a Fe I line. In the absence of this blend the amplitude of the Q/I signal might be larger.

⁶⁵ This polarization signal is quite wide. This may be due to the presence of a blending C₂ line.

⁶⁶ The large width of this polarization profile, and the fact that the peak does not fall at line center, suggest that the blending C₂ line might affect significantly this signal.

⁶⁷ The signal is somewhat noisy in this spectral region, and it is not possible to exclude that the signal might be classified as “W”.

⁶⁸ Very likely the overall structure of the polarization signal in the interval between 5204 Å and 5210 Å is due to quantum interferences between the J -levels of the term $^5\text{P}^{\circ}$. Both lines seem to show an “MS” structure partially hidden by blends.

⁶⁹ This line is severely blended with a Fe I line. In the absence of this blend the amplitude of the Q/I signal might be larger.

⁷⁰ This signal cannot be classified according to the scheme proposed in this work.

⁷¹ According to our scheme, this polarization signal has to be classified as “S”. However, it has to be remarked that its width is much larger than the width of any other signal of this class.

Table 2. Spectroscopic properties of the atomic spectral lines listed in Table 1, which present unambiguous identification and Q/I profile classification and measurement. The lines are collected element by element. The various quantities that are listed for each line are described in Sect. 3.

Elem.	λ^{Sun} (Å)	λ^{lab} (Å)	W_λ/λ (F)	Q/I (%)	Type	Multiplet	J	A (10^7 s^{-1})	E. low (cm^{-1})	E. high (cm^{-1})	g low	g high	Lower level	Coup. (%)
H I	4340.475	4340.468	659	0.12	W	$n = 2 - n = 5$ (1)		2.107	82 259.105	10 5291.651	1.000*	1.000*	PL?	
	6562.808	6562.817	649	0.110	S	$n = 2 - n = 3$ (1)		13.23	82 259.105	97 492.302	1.000*	1.000*	PL?	
Na I	5889.973	5889.953	120	0.309	MS	$3s^2S - 3p^2P^o$ (1)	1/2-3/2	6.16	0.00	16 973.379	2.000*	1.333*	GL	
	5895.940	5895.923	91.0	0.07	—		1/2-1/2	6.14	0.00	16 956.183	2.000*	0.667*	GL	
Mg I	5167.327	5167.3216	173	0.100	W	$3p^3P^o - 4s^3S$ (2)	0-1	1.13	21 850.368	41 197.37	0	2.000*	ML	
	3829.365	3829.3549	308	0.24	M1	$3p^3P^o - 3d^3D$ (3)	0-1	8.99	21 850.368	47 957.047	0	0.500*	ML	
	3832.310	3832.2996	600	0.125	M1		1-1	6.74	21 870.426	47 957.047	1.500*	0.500*	ML	
		3832.3037					1-2	12.1	21 870.426	47 957.018	1.500*	1.167*	ML	
	3838.302	3838.2918	641	0.11	M1		2-3	16.1	21 911.140	47 957.035	1.500*	1.333*	ML	
		3838.2943					2-2	4.03	21 911.140	47 957.018	1.500*	1.167*	ML	
		3838.290					2-1	0.448	21 911.140	47 957.047	1.500*	0.500*	ML	
	5528.418	5528.4094	53.8	0.052	W	$3p^1P^o - 4d^1D$ (9)	1-2	1.39	35 051.36	53 134.70	1.000*	1.000*	PL?	
Ca I	4703.003	4702.991	71.9	0.050	W	$3p^1P^o - 5d^1D$ (11)	1-2	2.19	35 051.36	56 308.43	1.000*	1.000*	PL?	
	4226.740	4226.728	342	1.955	M1	$4s^1S - 4p^1P^o$ (2)	0-1	21.76	0.00	23 652.324	0	1.000*	GL	
	4425.444	4425.441	31.6	0.110	S	$4p^3P^o - 4d^3D$ (4)	0-1	4.98	15 157.910	37 748.192	0	0.500*	ML	
	4283.014	4283.010	31.0	0.15	W	$4s^3P^o - 4p^3P$ (5)	1-2	4.339	15 210.067	38 551.588	1.500*	1.500*	ML	
	4307.748	4307.741	40.2	0.10	S		1-0	19.92	15 210.067	38 417.585	1.500*	0	ML	
Ca II	5598.491	5598.487	21.1	0.050	S	$4s^3D - 4p^3D^o$ (21)	1-1	4.272	20 335.344	38 192.373	0.501	0.500*	ML	
	3933.682	3933.664	4874	0.80	M1	$4s^2S - 4p^2P^o$ (1)	1/2-3/2	14.70	0.00	25 414.427	2.000*	1.333*	GL	
	3179.342	3179.332	182	0.35	W	$4p^2P^o - 4d^2D$ (4)	3/2-5/2	35.73	25 414.427	56 858.511	1.333*	1.200*	PL	
Sc II	3651.800	3651.798	39.1	0.10	W	$a^3D - z^3F^o$ (2)	2-2	2.511	67.68	27 443.65	1.17	0.65	ML	
	4246.837	4246.829	40.3	0.235	MS	$a^1D - z^1D^o$ (7)	2-2	15.44	2540.97	26 081.32	1.00	1.00	ML	
	5239.823	5239.823	10.5	0.069	S	$a^1S - z^1P^o$ (26)	0-1	1.374	11 736.35	30 815.65	0	1.00	ML	
Ti I	4536.054	4536.051	16.3	0.115*	S	$a^5F - y^5F^o$ (42)	1-1	6.814	6556.86	28 596.45	0.00	0.00	ML	
	4527.325	4527.305	14.8	0.070	S		1-2	2.204	6556.86	28 638.82	0.00	1.01	ML	
	4840.884	4840.874	12.6	0.054	S	$a^1D - y^1D^o$ (53)	2-2	1.762	7255.29	27 906.91	1.02	0.98	ML	

Table 2. continued.

Elem.	λ^{Sun} (Å)	λ^{Lab} (Å)	W_d/λ (F)	Q/I (%)	Type	Multiplet	J	A (10^7 s^{-1})	E. low (cm^{-1})	E. high (cm^{-1})	g low	g high	Lower level	Coup. (%)
Ti I	3308.399	3308.391	9.7	0.34*	S	$a^3P-t^3D^o$ (87)	0-1	7.898	8436.630	38 654.23	0	0.54	ML	
	4186.126	4186.119	10.0	0.26*	S	$a^1G-y^1G^o$ (129)	4-4	2.094	12 118.46	36 000.25	0.98	1.00	ML	
	3724.574	3724.570	23.1	0.155	S	$a^1G-x^1G^o$ (131)	4-4	9.067	12 118.46	38 959.53	0.98	1.02	ML	
	4639.368	4639.369	8.4	0.070	S	$a^5P-w^5D^o$ (145)	2-2	5.902	14 028.47	35 577.14	1.82	1.53	ML	
	4639.946	4639.944	7.3	0.060	S		1-1	6.633	13 981.75	35 527.76	2.50	1.51	ML	
	4453.710	4453.708	9.0	0.125	S	$a^3G-v^3G^o$ (160)	3-3	4.692	15 108.153	37 554.99	0.74	0.77	ML	
	4431.292	4431.284	1.1	0.22	S	$b^3P-r^3D^o$ (218)	0-1	1.769	17 995.75	40 556.07	0	0.49	ML	
	4599.227	4599.226	1.3	0.065	S	$c^3P-r^3D^o$	0-1	1.543	18 818.23	40 556.07	0	0.49	ML	
	5565.485	5565.476	2.9	0.119	S	$a^3H-y^1G^o$ (229)	4-4	1.408	18 037.28	36 000.25	0.80	1.00	ML	
	4868.263	4868.264	5.5	0.050	S	$a^3H-z^3P^o$ (231)	4-5	4.147	18 037.28	38 572.75	0.80	0.81	ML	
	4778.258	4778.259	3.3	0.056	S	$a^3H-x^1G^o$ (232)	4-4	1.955	18 037.28	38 959.53	0.80	1.02	ML	
	4742.798	4742.791	5.7	0.192	S	$a^3H-x^3H^o$ (233)	4-4	5.340	18 037.28	39 115.99	0.80	0.88?	ML	
	4758.124	4758.120	8.2	0.107	S		5-5	7.122	18 141.252	39 152.14	1.02	1.02	ML	
	4759.276	4759.272	8.6	0.097	S		6-6	7.394	18 192.594	39 198.39	1.17	1.18	ML	
	5644.146	5644.137	5.1	0.231	S	$b^1G-y^1G^o$ (240)	4-4	2.491	18 287.62	36 000.25	1.02	1.00	ML	
	4805.420	4805.416	7.7	0.063	S	$c^3P-s^3D^o$ (260)	2-3	5.825	18 911.55	39 715.51	1.54	1.31	ML	
	4796.189	4796.210	5.0	0.055	S		0-1	1.469	18 818.23	39 662.15	0	0.52	ML	
	4975.351	4975.344	3.6	0.095	S	$b^1D-w^1F^o$ (283)	2-3	6.097	20 209.64	40 303.04	1.01	1.05	ML	
	4237.891	4237.889	4.0	0.15	S	$b^1D-u^1D^o$ (284)	2-2	11.50	20 209.64	43 799.57	1.01	0.98	ML	
	5120.420	5120.420	6.0	0.080	S	$a^1H-z^1P^o$ (288)	5-6	4.692	20 795.65	40 319.80	1.01	1.03	ML	
Ti II	3372.812	3372.800	135.9	0.12	M0	$a^4F-z^4G^o$ (1)	5/2-7/2	11.09	93.94	29 734.45	1.029*	0.98	ML	
	3380.260	3380.278	31.2	0.10	W		9/2-9/2	1.570	393.22	29 968.08	1.333*	1.172*	ML	
	3383.765	3383.761	127	0.12	M0		3/2-5/2	10.94	0.00	29 544.37	0.400*	0.57	GL	
	3242.007	3241.984	83.0	0.15	M1	$a^4F-z^4F^o$ (2)	3/2-3/2	11.62	0.00	30 836.52	0.400*	0.40	GL	
	3234.518	3234.517	15.2	0.12	M1		9/2-9/2	13.81	393.22	31 300.92	1.333*	1.333*	ML	
	3761.320	3761.320	61.0	0.10	M1	$a^2F-z^2F^o$ (13)	5/2-5/2	9.887	4628.61	31 207.44	0.86	0.86	ML	
	3759.299	3759.291	115	0.10	W		7/2-7/2	9.345	4897.60	31 490.82	1.14	1.14	ML	
	3510.846	3510.840	29.1	0.12*	S	$b^2G-y^2G^o$ (88)	7/2-7/2	9.332	15 265.60	43 740.77	0.89	0.89	ML	
	3504.892	3504.890	37.6	0.14*	W		9/2-9/2	8.213	15 257.53	43 780.99	1.11	1.11	ML	

Table 2. continued.

Elem.	λ^{Sun} (Å)	λ^{Lab} (Å)	W_d/λ (F)	Q/I (%)	Type	Multiplet	J	A (10^7 s^{-1})	E. low (cm^{-1})	E. high (cm^{-1})	g low	g high	Lower level	Coup. (%)
Fe I	3476.712	3476.704	136	0.15	W	$a^5D-z^5P^o$ (6)	0-1	0.5425	978.074	29 732.749	0	2.487	ML	
	3465.880	3465.863	158	0.11	W		1-1	0.8455	888.132	29 732.749	1.498	2.487	ML	
-	3734.874	3734.867	945	0.205	W	$a^5F-y^5F^o$ (21)	5-5	9.014	6928.280	33 695.418	1.404	1.417	ML	
	3743.368	3743.364	193	0.100	W		2-1	2.602	7985.795	34 692.172	0.995	-0.016	ML	
	3749.495	3749.487	578	0.25	W		4-4	7.633	7376.775	34 039.540	1.349	1.344	ML	
	3758.245	3758.235	497	0.18	M1		3-3	6.336	7728.071	34 328.775	1.248	1.244	ML	
	3763.803	3763.790	255	0.21	M1		2-2	5.441	7985.795	34 547.235	0.995	0.998	ML	
	3767.204	3767.194	262	0.10	M1		1-1	6.393	8154.725	34 692.172	-0.014	-0.016	ML	
	3581.209	3581.195	599	0.16	M1		5-6	10.18	6928.280	34 843.980	1.404	1.332	ML	
	3586.990	3586.985	147	0.13	W		2-2	1.568	7985.795	35 856.424	0.995	0.335	ML	
	3608.869	3608.861	287	0.13	M1		1-2	8.131	8154.725	35 856.424	-0.014	0.335	ML	
	3618.777	3618.769	385	0.24	M1		2-3	7.272	7985.795	35 611.649	0.995	0.887	ML	
-	3585.714	3585.708	63.0	0.11	W	$a^5F-z^5G^o$ (23)	4-4	0.3745	7376.775	35 257.345	1.349	1.103	ML	
	3631.475	3631.464	369	0.10	M1		3-4	5.170	7728.071	35 257.345	1.248	1.103	ML	
	3647.851	3647.844	313	0.17	M1		4-5	2.913	7376.775	34 782.448	1.349	1.218	ML	
	3521.270	3521.264	110	0.13	W		4-4	0.2846	7376.775	35 767.591	1.349	1.100	ML	
	3570.134	3570.100	387	0.14	M1		4-5	6.763	7376.775	35 379.237	1.349	1.248	ML	
	3558.532	3558.518	137	0.18	W		2-3	0.5758	7985.795	36 079.395	0.995	0.791	ML	
	3565.396	3565.381	274	0.12	W		3-4	3.762	7728.071	35 767.591	1.248	1.100	ML	
	4383.557	4383.547	235	0.300	M1		4-5	4.998	11 976.260	34 782.448	1.254	1.218	ML	
	4404.761	4404.752	181	0.23	M1		3-4	2.753	12 560.953	35 257.345	1.086	1.103	ML	
	4415.135	4415.125	92.9	0.13	W		2-3	1.185	12 968.573	35 611.649	0.670	0.887	ML	
-	4271.774	4271.764	177	0.15	W	$a^3F-z^3G^o$ (42)	4-5	2.277	11 976.260	35 379.237	1.254	1.248	ML	
	4307.912	4307.906	165	0.10	W		3-4	3.397	12 560.953	35 767.591	1.086	1.100	ML	
	4325.775	4325.765	174	0.20	M1		2-3	4.973	12 968.573	36 079.395	0.670	0.791	ML	
	4045.825	4045.815	316	0.275	M1		4-4	8.622	11 976.260	36 686.204	1.254	1.246	ML	
	4071.749	4071.740	191	0.25	M1		2-2	7.645	12 968.573	37 521.186	0.670	0.688	ML	
	4063.605	4063.597	219	0.26	M1		3-3	6.776	12 560.953	37 162.770	1.086	1.086	ML	
	4233.612	4233.608	70.4	0.10	W		1-2	1.851	20 019.648	43 633.535	2.999	2.009	ML	
	4250.130	4250.125	79.5	0.14	W		2-3	2.075	19 912.511	43 434.633	2.008	1.755	ML	
	4235.949	4235.942	90.9	0.15	W		4-4	1.883	19 562.457	43 163.327	1.642	1.655	ML	
	4299.249	4299.242	49.3	0.10	W		4-5	1.218	19 562.457	42 815.855	1.642	1.585	ML	
-	3621.467	3621.463	40.6	0.10	W	$a^3G-y^3H^o$ (294)	4-5	5.067	21 999.167	49 604.45	1.051	1.075	ML	
	3594.638	3594.632	40.8	0.13	W		4-4	2.744	22 996.686	50 808.053	1.493	1.574	ML	

Table 2. continued.

Elem.	λ^{Sun} (Å)	λ^{lab} (Å)	W_λ/λ (F)	Q/I (%)	Type	Multiplet	J	A (10^7 s^{-1})	E. low (cm^{-1})	E. high (cm^{-1})	g low	g high	Lower level	Coup. (%)
Fe I	3554.937	3554.922	111	0.10	W	$z^7\text{F}^o\text{-}e^7\text{G}(326)$	5-6	16.99	22 845.880	50 967.873	1.498	1.415	ML	
	3533.014	3533.008	31.4	0.15	W		0-1	9.278	23 270.392	51 566.86	0	-0.374	ML	
	6024.068	6024.066	19.8	0.050*	S	$y^3\text{F}^o\text{-}f^5\text{G}(1178)$	4-5	1.267	36 686.204	53 281.735	1.246	1.221	PL	
Co I	3594.876	3594.870	25.7	0.11	W	$a^4\text{F}\text{-}z^4\text{F}^o(4)$	5/2-5/2	0.9212	1406.84	29 216.37	1.028	1.033	ML	
	3453.512	3453.514	87.9	0.12	W	$b^4\text{F}\text{-}y^4\text{G}^o(22)$	9/2-11/2	11.17	3482.82	32 430.59	1.336	1.287	ML	
	3405.126	3405.120	60.5	0.18	M0	$b^4\text{F}\text{-}y^4\text{F}^o(23)$	9/2-9/2	10.22	3482.82	32 841.99	1.336	1.313	ML	
Ni I	3624.733	3624.733	37.1	0.125	W	$a^3\text{F}\text{-}z^5\text{G}^o(2)$	4-5	0.02 594	0.00	27 580.411	1.250	1.28	GL	
	3602.287	3602.281	26.2	0.12	W	$a^3\text{F}\text{-}z^5\text{F}^o(3)$	3-4	0.04 431	1332.153	29 084.478	1.083	1.288	ML	
	3664.097	3664.095	43.8	0.11	W	$a^3\text{F}\text{-}z^3\text{P}^o(4)$	2-1	0.1990	2216.519	29 500.690	0.671	1.426	ML	
	3452.905	3452.890	73.1	0.19	W	$a^3\text{D}\text{-}z^5\text{F}^o(17)$	2-3	0.9827	879.813	29 832.810	1.149	1.208	ML	
	3461.667	3461.652	219	0.17	W		3-4	2.698	204.786	29 084.478	1.332	1.288	ML	
	3492.975	3492.956	239	0.10	W	$a^3\text{D}\text{-}z^3\text{P}^o(18)$	2-1	9.781	879.813	29 500.690	1.149	1.426	ML	
	3610.460	3610.462	52.0	0.19	W		2-2	0.7241	879.813	28 569.210	1.149	1.485	ML	
	3597.712	3597.705	50.2	0.17	M1		1-1	1.395	1713.080	29 500.690	0.497	1.426	ML	
	3458.467	3458.474	189	0.14	M1	$a^3\text{D}\text{-}z^3\text{F}^o(19)$	1-2	6.126	1713.080	30 619.440	0.497	0.740	ML	
	3515.066	3515.054	202	0.12	W		2-3	4.236	879.813	29 320.782	1.149	1.086	ML	
	3433.579	3433.558	143	0.10	W		3-3	1.727	204.786	29 320.782	1.332	1.086	ML	
	3446.271	3446.263	136	0.100	M1	$a^3\text{D}\text{-}z^3\text{D}^o(20)$	2-2	4.367	879.813	29 888.505	1.149	1.044	ML	
	3472.558	3472.545	136	0.135	W		2-3	1.223	879.813	29 668.918	1.149	1.300	ML	
	3674.150	3674.15	33.0	0.10	W	$a^1\text{D}\text{-}z^3\text{F}^o(32)$	2-2	0.2016	3409.925	30 619.440	1.014	0.740	ML	
	3619.400	3619.392	204	0.14	W	$a^1\text{D}\text{-}z^1\text{F}^o(35)$	2-3	6.630	3409.925	31 031.042	1.014	1.048	ML	
Cu I	3380.585	3380.574	239	0.100	W	$a^1\text{D}\text{-}z^1\text{P}^o(37)$	2-1	13.15	3409.925	32 982.280	1.014	1.005	ML	
	3485.110	3485.110	29.2	0.10*	S*	$z^5\text{F}^o\text{-}e^3\text{H}(118)$	3-4	3.382	29 832.810	58 518.11	1.208	0.800*	ML	
	3247.569	3247.540	76.0	0.93	M0	$4s^2\text{S}\text{-}4p^2\text{P}^o(1)$	1/2-3/2	13.70	0.00	30 783.686	2.000*	1.333*	GL	
	3273.972	3273.957	67.4	0.17	W		1/2-1/2	13.61	0.00	30 535.302	2.000*	0.667*	GL	
	5218.209	5218.202	9.8	0.052	S	$4p^2\text{P}^o\text{-}4d^2\text{D}(7)$	3/2-5/2	12.21	30 783.686	49 942.057	1.333*	1.200*	PL	
	5153.241	5153.235	8.5	0.110	S		1/2-3/2	10.34	30 535.302	49 935.200	0.667*	0.800*	PL	

Table 2. continued.

Elem.	λ^{Sun} (Å)	λ^{Lab} (Å)	W_d/λ (F)	Q/I (%)	Type	Multiplet	J	A (10^7 s^{-1})	E. low (cm^{-1})	E. high (cm^{-1})	g low	g high	Lower level	Coup. (%)
Sr I	4607.338	4607.331	7.8	1.080	S	$5s^2 \text{ } ^1\text{S}-5s5p \text{ } ^1\text{P}^o(2)$	0-1	20.1	0.00	21 698.482	0	1.000*	GL	
	4077.724	4077.714	100	0.905	MS	$5s^2 \text{ } ^2\text{S}-5p^2 \text{ } ^2\text{P}^o(1)$	1/2-3/2	14.2	0.00	24 516.65	2.000*	1.333*	GL	
Y I	4128.309	4128.31	2.9	0.305	S	$a^2 \text{D}-y^2 \text{D}^o(5)$	5/2-5/2	15.64	530.36	24 746.60	1.196	1.088	ML	
	4142.842	4142.86	5.3	0.165	S		3/2-3/2	15.75	0.00	24 131.20	0.798	0.823	GL	
Y II	3633.138	3633.13	19.0	0.27	S	$a^1 \text{S}-z^1 \text{P}^o(2)$	0-1	13.37	0.00	27 516.70	0	0.910	GL	
	3710.292	3710.30	27.2	0.15*	S	$a^3 \text{D}-z^3 \text{F}^o(7)$	3-4	15.52	1449.75	28 394.17	1.332	1.254	ML	
	3600.739	3600.74	19.2	0.10	W	$a^3 \text{D}-z^3 \text{D}^o(9)$	3-3	14.00	1449.75	29 213.95	1.332	1.333	ML	
	4374.944	4374.94	20.1	0.21	S	$a^1 \text{D}-z^1 \text{D}^o(13)$	2-2	10.07	3296.20	26 147.27	1.000	0.912	ML	
Zr I	3519.618	3519.60	2.6	0.13*	S	$a^3 \text{F}-x^3 \text{G}^o(13)$	2-3	7.175	0.00	28 404.26	0.66	0.79	GL	
	3601.198	3601.18	3.6	0.11*	S		4-5	13.79	1240.84	29 001.65	1.24	1.21	ML	
Zr II	3391.973	3391.96	20.0	0.10	W	$a^4 \text{F}-z^4 \text{G}^o(1)$	9/2-11/2	14.02	1322.91	30 795.74	1.324	1.275	ML	
	3273.052	3273.04	23.9	0.19	W	$a^4 \text{F}-z^4 \text{F}^o(3)$	9/2-9/2	3.119	1322.91	31 866.49	1.324	1.321	ML	
	3556.597	3556.61	7.0	0.14*	S	$b^4 \text{F}-z^4 \text{F}^o(9)$	9/2-9/2	7.275	3757.66	31 866.49	1.326	1.321	ML	
	5112.279	5112.28	1.6	0.050	S	$b^2 \text{D}-y^2 \text{D}^o(95)$	3/2-3/2	1.639	13 428.50	32 983.73	0.800	0.810	ML	
Nb II	3260.552	3260.561	6.1	0.15*	S	$b^3 \text{H}-z^3 \text{I}^o$	4-5	12.47	17 469.77	48 130.50	0.880	0.870	ML	
Ru I	3728.042	3728.030	20.0	0.10*	S*	$a^5 \text{F}-z^5 \text{F}^o(2)$	5-5	7.935	0.00	26 816.23	1.397	1.394	GL	
	3742.278	3742.280	2.4	0.125*	S		2-2	5.606	2713.24	29 427.32	1.000	1.164	ML	
	3589.222	3589.215	5.7	0.100	S	$a^5 \text{F}-z^5 \text{G}^o(4)$	1-2	8.221	3105.49	30 958.80	0.000	0.375	ML	
Pd I	3553.095	3553.10	3.4	0.185*	S	$5s \text{ } ^1 \text{D}-5p^1 \text{P}^o(9)$	2-3	26.16	11 721.77	39 858.33	1.040	1.081	ML	
Ba I	5535.51	5535.484	-	0.133	S	$6s^2 \text{ } ^1 \text{S}-6s6p^1 \text{P}^o(2)$	0-1	11.9	0.00	18 060.264	0	1.02	GL	
Ba II	4554.036	4554.033	36.7	0.65	MS	$6s^2 \text{ } ^2 \text{S}-6p^2 \text{ } ^2 \text{P}^o(1)$	1/2-3/2	11.1	0.00	21 592.422	1.974	1.32	GL	
	3891.781	3891.781	11.6	0.14*	S	$6p^2 \text{ } ^2 \text{P}^o-6d^2 \text{ } ^2 \text{D}(4)$	1/2-3/2	21.7	20 261.562	45 949.496	0.672	0.79	-	
	4130.657	4130.648	10.9	0.27*	S		3/2-5/2	21.8	21 952.422	46 154.89	1.32	1.18	PL	

Table 2. continued.

Elem.	λ^{Sun} (Å)	λ^{lab} (Å)	W_λ/λ (F)	Q/I (%)	Type	Multiplet	J	A (10^7 s^{-1})	E. low (cm^{-1})	E. high (cm^{-1})	g low	g high	Lower level	Coup. (%)
La II	4354.436	4354.40	3.4	0.100*	S	$a^1\text{S}-y^1\text{P}^{\circ}(58)$	0–1	3.706	7394.57	30 353.33	0	1.074	ML	75–49
Ce II	4572.284	4572.277	3.3	0.075	S	$6s^4\text{H}-6p(5,1/2)^{\circ}$	11/2–11/2	2.663	5513.709	27 378.515	1.125	1.005	ML	82–87
	4460.225	4460.213	6.0	0.160	S	$6s^4\text{H}-6p(4,1/2)^{\circ}$	7/2–7/2	6.210	3854.012	26 268.203	0.669	0.712	ML	95–75
	4115.376	4115.374	2.7	0.135	S	$6s^4\text{F}-6p(2,3/2)^{\circ}$	3/2–3/2	9.397	7454.951	31 747.243	0.407	0.860	ML	95–95
	4062.232	4062.223	1.5	0.16	S	$6s^2\text{G}-6p(4,3/2)^{\circ}$	7/2–7/2	9.253	11 015.579	35 625.700	1.016	0.923	ML	49–48
	4222.602	4222.599	5.2	0.12*	S	$5d^2\text{I}^{\circ}-6p^2\text{H}$	9/2–9/2	1.869	987.611	24 663.053	0.948	0.933	ML	30–34
	4486.914	4486.909	2.5	0.13	S	$6s^2\text{G}^{\circ}-6p^2\text{H}$	9/2–9/2	1.112	2382.246	24 663.053	1.039	0.933	ML	33–34
	4083.226	4083.233	6.4	0.15	S	$6s^4\text{H}^{\circ}-6p^4\text{H}$	11/2–11/2	4.282	5651.357	30 134.910	1.085	1.146	ML	49–53
Nd II	4109.450	4109.455	9.5	0.12	S	$6s^6\text{I}-6p^6\text{K}^{\circ}(10)$	13/2–15/2	4.923	2585.453	26 912.765	1.150	1.130	ML	87–
	4462.993	4462.985	2.9	0.11	S	$6s^4\text{I}-6p^6\text{K}^{\circ}(50)$	13/2–15/2	2.458	4512.481	26 912.765	1.110	1.130	ML	87–
	3784.252	3784.250	5.8	0.27	S	$6s^4\text{I}-6p^4\text{I}^{\circ}$	11/2–11/2	9.522	3066.750	29 484.600	0.980	1.022	ML	80–
Sm II	3230.592	3230.559	10.5	0.21*	S*	$a^8\text{F}-146^{\circ}(21)$	7/2–9/2	1.804	1489.116	32 434.70	1.610	1.455	ML	97–
Eu II	4129.724	4129.73	12.1	0.180	S	$a^9\text{S}^{\circ}-z^9\text{P}(1)$	4–4	6.947	0.00	24 207.86	1.984	1.877	GL	–63
Gd II	3439.229	3439.208	3.5	0.13*	S	$a^8\text{D}^{\circ}-^8\text{F}$	5/2–5/2	10.30	3082.011	32 150.143	2.044	1.81	ML	79–77
Dy II	3407.805	3407.796	18.8	0.10*	S*	$6s^6\text{I}-6p^6\text{I}^{\circ}$	17/2–17/2	3.603	0.00	29 336.06	1.290	1.268	GL	95–52
	3694.817	3694.810	9.2	0.10*	S	$6s^4\text{I}-5d^2\text{I}^{\circ}$	15/2–15/2	2.586	828.31	27 885.60	1.203	1.251	ML	72–21
Yb I	3987.966	3987.98	5.0	0.11*	S	$6s^2\text{I}^{\circ}\text{S}-6s6p\text{I}^{\circ}\text{P}^{\circ}(2)$	0–1	17.6	0.00	25 068.222	0	1.035	GL	99–73