A KEY PHYSICAL MECHANISM FOR UNDERSTANDING THE ENIGMATIC LINEAR POLARIZATION OF THE SOLAR Ba ii AND Na i D1 LINES

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ABSTRACT

The linearly polarized spectrum of the solar limb radiation produced by scattering processes is of great diagnostic potential for exploring the magnetism of the solar atmosphere. This spectrum shows an impressive richness of spectral details and enigmatic Q/I signals, whose physical origin must be clearly understood before they can be exploited for diagnostic purposes. The most enduring enigma is represented by the polarization signals observed in the D1 resonance lines of Na i (5896 Å) and Ba ii (4934 Å), which were expected to be intrinsically unpolarizable. The totality of sodium and 18% of barium have hyperfine structure (HFS), and it has been argued that the only way to produce a scattering polarization signal in such lines is through the presence of a substantial amount of atomic polarization in their lower HFS levels. The strong sensitivity of these long-lived levels to depolarizing mechanisms led to the paradoxical conclusion that the observed D1-line polarization is incompatible with the presence in the lower solar chromosphere of inclined magnetic fields sensibly stronger than 0.01 G. Here we show that by properly taking into account the fact that the solar D1-line radiation has a non-negligible spectral structure over the short frequency interval spanned by the HFS transitions, it is possible to produce scattering polarization signals in the D1 lines of Na i and Ba ii without the need of ground-level polarization. The resulting linear polarization is not so easily destroyed by elastic collisions and/or magnetic fields.

Key words: atomic processes – line: profiles – polarization – radiative transfer – scattering – Sun: chromosphere

1. INTRODUCTION

When observed with high-sensitivity spectropolarimeters, the linearly polarized spectrum of the solar radiation coming from quiet regions close to the limb (the so-called “second solar spectrum”) reveals a complex structure and an impressive richness of spectral details (Stenflo & Keller 1997). We know that the second solar spectrum is the observational signature of atomic polarization (i.e., population imbalances and quantum interference between different magnetic sublevels), produced by the absorption and scattering of anisotropic radiation. However, the physics of scattering polarization in an optically thick plasma, such as the extended solar atmosphere, is very complicated and a general theory for multilevel systems is still lacking. It is thus natural that many of the Q/I signals of the second solar spectrum were considered as enigmatic by their discoverers, as well as a true challenge for the theorists (see the review by Trujillo Bueno 2009). At present, the most challenging Q/I signals are those observed in the D1 lines of Na i and Ba ii at 5896 Å and 4934 Å, respectively (see Figures 2 and 5 of Stenflo & Keller 1997). The aim of this Letter is to point out a physical mechanism that might be of key importance for explaining such enigmatic linear polarization profiles.

The polarization signals observed by Stenflo & Keller (1997) and Stenflo et al. (2000) in the D1 lines of Na i and Ba ii were considered enigmatic because these lines were expected to be intrinsically unpolarizable. This is because they result from transitions between an upper and a lower level with \( J = 1/2 \) (\( J \) being the total angular momentum). Such levels cannot carry atomic alignment, so that no linear polarization can, in principle, be produced in these lines in weakly magnetized regions of the solar atmosphere. However, 100% of sodium and about 18% of barium have hyperfine structure (HFS). Both sodium (\(^{23}\)Na) and the barium isotopes with HFS (\(^{135}\)Ba and \(^{137}\)Ba) have nuclear spin \( I = 3/2 \). In such isotopes, the upper and lower \( J \)-levels of the D1 line transition thus split into two HFS F-levels (\( F = 1 \) and \( F = 2 \), with \( F \) the total, electronic plus nuclear, angular momentum), which can carry atomic alignment. In fact, taking the HFS of sodium into account, Landi Degl’Innocenti (1998) concluded that if there is a substantial amount of atomic alignment in the ground level (i.e., in the lower \( F = 1 \) and \( F = 2 \) levels of the sodium D1 and D2 lines), then a significant Q/I signal is produced in the D1 line. In his investigation of the sodium doublet, Landi Degl’Innocenti (1998) considered the unmagnetized case and assumed frequency-coherent scattering and a constant pumping radiation field within each D-line.

In Landi Degl’Innocenti’s (1998) modeling of the sodium D1 line, the ensuing Q/I profile vanishes if the alignment of the ground F-levels is destroyed. Such lower F-levels are long-lived and therefore their atomic alignment is very sensitive to depolarizing mechanisms, such as elastic collisions with neutral hydrogen atoms and/or the Hanle effect of very weak (mG) non-vertical magnetic fields. Accordingly, Landi Degl’Innocenti (1998) concluded that the Q/I signal detected by Stenflo & Keller (1997) in the sodium D1 line implies that depolarization does not occur in the lower solar chromosphere (where the line-core of the sodium D-lines originates), which would seem to rule out the existence of tangled magnetic fields and of inclined, canopy-like fields stronger than 0.01 G. He also pointed out

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5 An atomic level is said to be aligned when sublevels with different values of \( |M| \) (being the magnetic quantum number) are unevenly populated. When the upper and/or lower level of a line transition is aligned, then the emergent radiation is, in general, linearly polarized, even in the absence of a magnetic field (e.g., Landi Degl’Innocenti & Landolfi 2004).
that this is difficult to understand because there is substantial evidence from other types of observations for both types of magnetic field. This paradox was later reinforced by detailed theoretical investigations on the magnetic sensitivity of the D lines of Na i (Trujillo Bueno et al. 2002; Casini et al. 2002) and of Ba ii (Belluzzi et al. 2007), as well as on the depolarizing role of elastic collisions with neutral hydrogen atoms (Kerkeni & Bommier 2002). It is also noteworthy that the scattering polarization profile obtained by Landi Degl’Innocenti (1998) is antisymmetric, in contrast with the symmetric peak observed by Stenflo & Keller (1997), but in agreement with the observations of other researchers (see Trujillo Bueno 2009 for a review).

The physical mechanism discussed in this Letter does not require the presence of atomic polarization in the lower level. Indeed, we will show that by properly taking into account HFS and partial frequency redistribution (PRD) effects, even without any atomic polarization in the (long-lived) lower $F$-levels, the scattering of anisotropic $D_1$-line radiation in the solar atmosphere can produce significant linear polarization in the $D_1$ lines of Ba ii and Na i.

2. THE PHYSICAL PROBLEM

We model the intensity and linear polarization profiles of the $D_1$ lines of Ba ii and Na i by solving the full non-LTE radiative transfer problem for polarized radiation in one-dimensional semi-empirical models of the solar atmosphere, taking PRD effects into account. To this aim, we apply the redistribution matrix approach outlined in Belluzzi & Trujillo Bueno (2012), which can be applied also to the case of a two-level atom with HFS, under the assumptions that the lower $F$-levels are unpolarized and infinitely sharp. As previously discussed, these approximations appear to be suitable since the lower level of the $D_1$ lines of Ba ii and Na i is the (long-lived) ground level. We recall that our redistribution matrix is given by the linear combination of two terms, which describe purely coherent scattering ($R_0$) and completely redistributed scattering ($R_{ii}$) in the atom rest frame, respectively.

We investigate the $D_1$ line of barium accounting for the contribution of all its seven stable isotopes. The two odd isotopes ($^{139}$Ba and $^{141}$Ba, both with nuclear spin $I = 3/2$) are described through a two-level model atom with HFS, the five even isotopes (about 82.18% in abundance) are described through a two-level model atom without HFS. The $D_1$ line of sodium is modeled through a two-level model atom with HFS (sodium has a single stable isotope, $^{23}$Na, with $I = 3/2$).

As clear from the Grotrian diagram shown in the left panel of Figure 1, in the isotopes with HFS, each upper $F$-level can be excited from the two lower $F$-levels through two transitions that are very close in frequency (about 70 mÅ apart in the barium isotopes with HFS, and about 20 mÅ apart in sodium). Due to such small frequency separation, the assumption that the pumping radiation field is the same in the two HFS transitions appears to be an excellent approximation for modeling these lines. However, under this hypothesis, and assuming that the lower level is unpolarized, no atomic polarization can be produced in the upper $F$-levels, and therefore no polarization can be obtained in the emergent radiation. This can be seen, for example, from the statistical equilibrium equations for a two-level atom with HFS derived in Landi Degl’Innocenti & Landolfi (2004, hereafter LL04). Under the hypothesis of unpolarized lower level, such equations can be analytically solved and the multipole components of the density matrix of the upper levels result to be given by

$$\rho^K_Q(F_u, F'_u) = \frac{N_f}{N} \times \frac{3(2F_u + 1)(2F'_u + 1)}{2I + 1} \times \frac{B(J_u \rightarrow J_l)}{A(J_u \rightarrow J_l) + 2\pi i v_{F_u, F'_u}} \sum_{F_i} (-1)^{i+F_{l}+F_{u}+Q} \times (2F_{l} + 1) \times \left\{ \frac{1}{J_u J_l K} \times \left\{ \begin{array}{ccc} J_u & J_l & K \\ F_u & F'_u & I \end{array} \right\} \times \left\{ \begin{array}{ccc} J_u & J_l & K \\ F_u & F'_u & I \end{array} \right\} \right\} J^K_{Q}(v_0),$$

where $A(J_u \rightarrow J_l)$ and $B(J_u \rightarrow J_l)$ are the Einstein coefficients for spontaneous emission and for absorption, respectively, $N$ is the total number density of atoms, $N_f$ is the number density of atoms in the lower $J$-level, and $v_{F_u, F'_u}$ is the frequency separation between the HFS levels $F_u$ and $F'_u$. Since the incident field (described in Equation (1) through the radiation field tensor $J^K_{Q}(v_0)$, see Equation (5.157) of LL04) is assumed to be constant across the various HFS transitions (this is one of the hypotheses the theory described in LL04 is based on), it is possible to perform the sum over $F_u$, thus obtaining

$$\rho^K_Q(F_u, F'_u) = \frac{N_f}{N} \times \frac{3(2F_u + 1)(2F'_u + 1)}{2I + 1} \times \frac{B(J_u \rightarrow J_l)}{A(J_u \rightarrow J_l) + 2\pi i v_{F_u, F'_u}} (-1)^{i-J_{l}+1+F_{l}+K+Q} \times \left\{ \begin{array}{ccc} J_u & J_l & K \\ F_u & F'_u & I \end{array} \right\} J^K_{Q}(v_0).$$

Observing that the first 6-$j$ symbol in the second line of Equation (2) vanishes for $J_u = 1/2$ and $K = 2$, we immediately see that under the above-mentioned hypotheses, no atomic polarization (either alignment or $F$-state interference, both being described by the multipole components with $K = 2$) can be induced in the upper $F$-levels of the $D_1$ line transition. Indeed, in the previous investigations on this line, in which the pumping radiation field was assumed to be identical in the various HFS transitions, either because the investigation was carried out by applying the complete frequency redistribution (CRD) theory presented in LL04 (see Trujillo Bueno et al. 2002), or because this was assumed by definition, though considering coherent scattering (see Landi Degl’Innocenti 1998), the authors concluded that the only way to obtain a scattering polarization signal in the core of the $D_1$ line is by assuming that a given amount of atomic polarization is present in the lower level.

In this investigation, on the contrary, we neglect lower level polarization but we take into account, through the $R_0$ term of the redistribution matrix, that the pumping radiation field can, in principle, be different in the various HFS transitions (see the right panel of Figure 1 for the case of barium). Although such difference is in many cases very small, we find that this allows atomic polarization to be induced in the upper $F$-levels, giving rise to an appreciable polarization signal in the core of the $D_1$ line (see the next section). According to this physical mechanism, the amplitude of the linear polarization signal produced in the $D_1$ line is expected to be higher when the HFS splitting of the lower level is larger.

The two-level atom models (either with or without HFS) considered in this investigation do not allow us to take quantum interference between the upper $J$-levels of the $D_1$ and $D_2$ lines
Figure 1. Left panel: Grotrian diagram showing the fine structure (FS) and HFS levels considered in our atomic models of sodium and of the barium isotopes with HFS (splittings are not drawn to scale). The FS and HFS components of the D₁-line transition are drawn on the diagram. Right panel: anisotropy (expressed through the ratio between the $J_0^2$ and $J_0^0$ components of the radiation field tensor) of the solar radiation across the Ba II D₁ line at 800 Km in the FAL-C model atmosphere (the height where the line center optical depth is unity for a LOS with $\mu = 0.1$). The vertical lines indicate the wavelength positions of the four HFS components of $^{137}$Ba and of the FS component of $^{138}$Ba.

Figure 2. Left: intensity (upper panel) and $Q/I$ (lower panel) profiles of the Ba II D₁ line, as calculated by applying the CRD theory presented in LL04, considering the FAL-C atmospheric model, and a LOS with $\mu = 0.1$. The solid line represents the solution obtained by considering the contribution of all the seven isotopes of barium. The dotted line represents the solution obtained by assuming that 100% of barium is $^{138}$Ba (which is devoid of HFS). Right: same as left panels, but for PRD calculations.

into account. This physical ingredient can actually be safely neglected for the investigation of the Ba II D₁ line, since it is about 380 Å away from D₂, but it is known to play an important role in the modeling of the Na I D-lines, which are only 6 Å apart. On the other hand, an accurate modeling of the scattering polarization in the Ba II D₁ and D₂ lines would require to account for the radiative and collisional coupling of the upper levels of such lines with the metastable $^2$D₃/₂ and $^2$D₅/₂ levels. This coupling, which is not present in neutral sodium since it does not have such metastable levels, cannot be accounted for within our two-level atom modeling. As we shall see below, in spite of such limitations, our approach is suitable to show that the physical mechanism identified in this investigation might be of key relevance for understanding the enigmatic D₁ line polarization.

3. RESULTS

Figure 2 shows the emergent Stokes $I$ and $Q/I$ profiles of the Ba II D₁ line calculated in the semi-empirical model C of Fontenla et al. (1993; hereafter, FAL-C model).
The profiles in the left panel of Figure 2 have been calculated in the limit of CRD, following the theoretical approach of LL04. As discussed in Section 2, within the framework of such theory, the absorption of radiation from an unpolarized lower level cannot induce any atomic polarization in the upper F-levels and therefore the D1 line must behave as intrinsically unpolarizable. Indeed, as shown in the lower left panel of Figure 2, the D1 line only produces a depolarization of the continuum polarization level (our calculations account for the contribution of a coherent polarized continuum).

The right panels of Figure 2 show the results of PRD calculations. In this case, through the $R_{11}$ term of the redistribution matrix, we account for the exact frequency dependence of the pumping radiation field within the D1 line. As expected, no signal is obtained if only $^{138}$Ba (which is devoid of HFS) is considered (see the dotted line). However, if the contribution of the small fraction ($\sim 18\%$) of the barium isotopes with HFS is taken into account, a conspicuous polarization signal is obtained for a line-of-sight (LOS) with $\mu = 0.1$ ($\mu$ being the cosine of the heliocentric angle). The $Q/I$ signal shows a large positive peak (about 0.45%) slightly blueshifted with respect to the line center, and a smaller negative peak (about $-0.15\%$) slightly redshifted. Such $Q/I$ peaks decrease, though remaining significant, for larger $\mu$ values.

As can be noted by comparing the top panels of Figure 2, the Stokes $I$ profile is not very sensitive to PRD effects, except at the very line center where the PRD calculation gives slightly smaller intensity values. Particularly interesting, on the other hand, is the significant broadening of the Stokes $I$ profile produced by the small fraction of barium isotopes with HFS (compare the solid and dotted lines).

The results of Figure 3 are also noteworthy. The bottom panel shows the $Q/I$ profiles calculated in three different semi-empirical models of the solar atmosphere (the temperature structure of such models is plotted in the upper panel). As can be observed, the $Q/I$ signals are not very different. This small sensitivity to the thermal model is good news, because the $Q/I$ signal of the Ba ii D1 line produced by the physical mechanism discussed in Section 2 is sensitive to the upper-level Hanle effect and therefore to magnetic fields in the gauss range.

In Figure 4, we show the results that we have obtained for the D1 line of NaI. The sensitivity of the $Q/I$ signal of this stronger line to the thermal model is more noticeable, with the (relatively cool) FAL-X model producing the largest peaks. Such $Q/I$ peaks are much weaker than those observed by Stenflo & Keller (1997) and than those obtained in the Ba ii D1 line. The calculated $Q/I$ signals are much weaker in sodium than in barium because the HFS splitting of the ground level is about four times smaller in NaI.

4. CONCLUDING COMMENTS

Two physical mechanisms able to produce a scattering polarization signal in the NaI and Ba ii D1 lines have been identified up to now. HFS is a fundamental ingredient in both of them. Such physical mechanisms are not mutually exclusive, and are probably at work simultaneously in the solar atmosphere, especially in the case of the NaI D1 line.

One mechanism is that pointed out by Landi Degl’Innocenti (1998), which requires the presence of a substantial amount of ground-level polarization. As clarified by Trujillo Bueno et al. (2002), this mechanism, which operates even when the pumping radiation is constant within the D lines (see also Casini et al. 2002), requires taking into account the absorption of anisotropic radiation in the D2 line (whose upper level has $J = 3/2$) and to assume that depolarizing mechanisms do not completely destroy the atomic alignment that repopulation pumping produces in the long-lived lower F-levels. Under such circumstances, the atomic alignment of the lower and upper F-levels of the D1 line (and
therefore its scattering polarization signal) are sensitive to the same (mG) magnetic field strengths.

In this Letter, we have shown that the absorption and scattering of anisotropic D1-line radiation within the solar atmosphere can directly produce linear polarization in the D1 line, without any need for ground-level polarization. This is possible if one takes into account that the solar D1-line radiation has a non-negligible spectral structure over the short frequency interval spanned by the HFS transitions. The fact that small variations of the pumping radiation field between very close HFS transitions is able to create a significant amount of atomic polarization in the upper F-levels of the D1 lines is certainly an unexpected and important result. The resulting Q/I signals are not so easily destroyed by elastic collisions and/or magnetic fields.

The amplitude and shape of the calculated Q/I profile of the BaII D1 line are similar to the observed ones⁶ (see Figure 5 of Stenflo & Keller 1997). The main discrepancy concerns the slightly redshifted peak, which reaches a negative value in the theoretical profile, while it remains positive in the observation. In our opinion, such discrepancy does not invalidate our conclusion that the physical mechanism we have discussed in this Letter may be a key ingredient for explaining the enigmatic linear polarization of the BaII D1 line. This is because our BaII model atom does not include the metastable 2D3/2 and 2D5/2 levels, which may have a significant impact on the D1 line polarization (see Manso Sainz & Trujillo Bueno 2003 concerning the CaII IR triplet).

The amplitudes of the Q/I profiles observed in the D1 lines of NaI and BaII are of the same order of magnitude, but the calculated Q/I signal of the NaI D1 line is one order of magnitude smaller. This is due to the fact that the HFS splitting of the ground level of sodium is four times smaller than that of barium. We believe that this discrepancy with the observation does not rule out the possibility that the physical mechanism described in this Letter may play a key role also for explaining the enigmatic linear polarization of the NaI D1 line. We plan to include in our modeling the quantum interference between the F-levels pertaining to the two upper J-levels of the sodium doublet. This additional physical ingredient will probably influence the shape of the Q/I profile, even in the neighborhood of the sodium D1 line core. In addition to this, we believe that if there is a non-negligible amount of ground-level polarization, then the physical mechanism discussed in this Letter should induce a larger Q/I signal.

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⁶ Although the calculated amplitude is, in reality, larger than the observed one, they can be easily brought into reasonable agreement by taking into account the spectral smearing produced by the limited spectral resolution of the observation and/or depolarizing mechanisms.