Modeling the Scattering Line Polarization of the Ca II Infrared Triplet


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Abstract. This paper describes in some detail our theoretical modeling of the "enigmatic" linear polarization signals of the infrared triplet lines of Ca II, which have been observed close to the solar limb using high-sensitivity spectropolarimeters. We demonstrate that the observed polarization amplitudes can be explained only if the metastable levels \( ^2\text{D}_{3/2} \) and \( ^2\text{D}_{5/2} \) are polarized. In particular, we show that the significant linear polarization observed in the 8662 Å line is fully due to dichroism in the solar atmosphere. We have applied the density matrix polarization transfer theory and solved numerically the relevant kinetic and transfer equations for a 5-level model atom taking into account all the relevant radiation pumping processes. The results of our multilevel scattering polarization calculations explain the relative amplitudes of the observed linear polarization in the Ca II IR triplet.

1. Introduction

Recently, Stenflo, Keller & Gandorfer (2000) have presented some "enigmatic" scattering polarization observations of the Ca II IR triplet. These authors measured the fractional linear polarization \( (Q/I) \) on the disc at few arcsec from the solar limb and found that the 8542 Å and 8662 Å lines have significant and similar positive polarization (of the order of 0.1 %), while the linear polarization amplitude of the 8498 Å line was substantially smaller. They consider their \( Q/I \) observations as "enigmatic" mainly because of the significant polarization amplitude found for the 8662 Å line, which they think is intrinsically unpolarizable according to the quantum numbers of the line transition. Such spectropolarimetric observations have been confirmed and extended to the four Stokes parameters by Dittmann et al. (2001) using the Gregory Coudé Telescope at the Observatorio del Teide (Tenerife). The present paper describes our theoretical explanation of such "enigmatic" spectropolarimetric observations.

The atomic model of Fig. 1 is sufficiently realistic for investigating the physical origin of the observed polarization in the infrared triplet of Ca II. Since calcium has no hyperfine structure splitting we can guarantee that the following

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atomic levels cannot harbor any atomic alignment: the lower-level of the H and K lines (which has angular momentum $J_1 = 1/2$) and the common upper level of the H line and of the 8662 Å line (which also has angular momentum $J_4 = 1/2$). In other words, the only levels of the model atom of Fig. 1 which can have in principle atomic alignment are the upper level of the K line (which is also the upper level of the 8498 Å and 8542 Å lines) and the two lower levels of the Ca II IR triplet, which are the metastable levels $^2D_{3/2}$ and $^2D_{5/2}$.

In section 2 we investigate what happens if we neglect the atomic polarization of the $^2D_{3/2}$ and $^2D_{5/2}$ levels while in section 3 we take it into account considering the generation and transfer of atomic polarization in the aforementioned 5-level model of Ca II. In both cases we assume an isothermal solar model atmosphere with T=6000 K. In section 4 we make a step further by showing the emergent $Q/I$ limb profiles in “realistic” solar atmospheric models: FAL-C and COOL-C. Finally, section 5 gives our conclusions.

2. Neglecting the atomic polarization of the $^2D_{3/2}$ and $^2D_{5/2}$ levels

Since the two levels of the 3 $^2D$ term are metastable (radiative transitions to the ground-level are forbidden due to selection rules), we could begin arguing (on the basis of their long lifetimes) that such metastable levels are totally depolarized by elastic collisions. Following this line of reasoning we shall assume, for the moment, that the lower levels of the Ca II IR triplet are completely depolarized. We shall find that under such a hypothesis we are not able to reproduce the observed $Q/I$ signals and that some metastable-level atomic alignment must survive somehow.

The transfer equations for the Stokes $I$ and $Q$ parameters can be deduced from the Density Matrix Polarization Transfer Theory (see Landi Degl’Innocenti, 1983; 1984). They are given exactly by Eqs. (1) and (2) of Trujillo Bueno (1999), which we reproduce here for convenience:

$$\frac{d}{ds} I = \epsilon_I - \eta_I I,$$
$$\frac{d}{ds} Q = \epsilon_Q - \eta_I Q,$$  \hspace{1cm} (1), (2)

where $\eta_I = \chi_I \phi_\nu \rho^0_\nu(t)$ and

$$\epsilon_I = \epsilon_I \phi_\nu \left[ \rho^0_0(u) + \mathcal{W} \frac{1}{2\sqrt{2}} (3\mu^2 - 1) \rho^2_0(u) \right],$$
$$\epsilon_Q = \epsilon_I \phi_\nu \left[ \mathcal{W} \frac{3}{2\sqrt{2}} (\mu^2 - 1) \rho^2_0(u) \right],$$  \hspace{1cm} (3), (4)

$^2$See the review by Trujillo Bueno (2001) for the meaning of the atomic alignment of a given atomic level of total angular momentum $J$ and for understanding why it is zero if $J = 0$ or $J = 1/2$. 

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Figure 1. Grotrian diagram of a 5-levels model for CaII

being $\chi_l = (\hbar \nu_0 / 4\pi) B_{ll} N \sqrt{2J_l + 1}$, $\epsilon_l = (\hbar \nu_0 / 4\pi) A_{ll} N \sqrt{2J_u + 1}$, $\mu$ the cosines of the angle formed by the ray and the vertical to the atmosphere, $\phi_\nu$ the line profile, $\hbar$ the Planck constant, $\nu_0$ the Bohr frequency of the transition, $N$ the total number density of atoms and $B_{ll}$ and $A_{ll}$ the Einstein coefficients for absorption and spontaneous emission. The coefficient $\mathcal{W}$ only depends on the total angular momentum values of the levels involved in the transition. Its numerical value is $\mathcal{W} = -0.5657$ for the 8498 line, $\mathcal{W} = 0.1414$ for the 8542 line and $\mathcal{W} = 0$ for the 8662 line (which is not surprising because the upper-level of the 8662 Å line has $J_u = 1/2$ and cannot be polarized). Finally, $\rho_0(J)\sqrt{2J+1}$ is the atomic population of each level of angular momentum $J$ and $\rho_0(J_5 = 3/2)$ is the atomic alignment of the upper level of the 8498 and 8542 lines.\(^3\)

Since we are assuming that all the atomic levels except the uppermost one are unpolarized, the statistical equilibrium (SE) equations for $\rho_0(J_5 = 3/2)$ and for the five $\rho_0$ elements can be easily derived by just adding to the standard SE equations for the populations an extra SE equation for $\rho_0(J_5 = 3/2)$. This extra equation can be obtained as a sum of three terms (one for each of the three transitions involving this level), and each one of them having exactly the same structure as in the two-level atom case with unpolarized lower-level (see Trujillo Bueno & Manso Sainz 1999).

We have solved numerically the coupled set of radiative transfer and SE equations applying the iterative methods mentioned below. The line of Fig. 2 labeled “5” shows the alignment of the uppermost level of the Ca II model atom for a non-magnetic isothermal atmosphere with T=6000 K. The upper panels of Fig. 3 show the corresponding emergent $Q/I$ profiles at $\mu = 0.1$. We see that they do not reproduce neither quantitatively nor qualitatively the

\(^3\)See Trujillo Bueno (2001) for an introduction to atomic polarization and optical pumping.
observations reported by Stenflo et al. (2000) and by Dittmann et al. (2001). For instance, the line at 8542 Å has opposite sign to the observed signal. The most dramatic disagreement is that $Q/I = 0$ for the 8662 Å line, while the above-mentioned observations show that the 8542 Å and 8662 Å lines have similar line-core polarization amplitudes (of the order of 0.1%). The reason for having obtained $Q/I = 0$ for the 8662 Å line is that, in the absence of lower-level atomic polarization, any $Q/I$-signal can only come from the emissivity term (see Eq. [2]). Since the upper-level is intrinsically unpolarizable, $\epsilon_Q$ must be zero. In fact, $W = 0$ for a $3/2 \rightarrow 1/2$ transition, which implies that $\epsilon_Q = 0$ according to Eq.(4).

3. Taking into account the atomic polarization of the $^2D_{3/2}$ and $^2D_{5/2}$ levels

Let us now allow for the possibility that the lower-level depopulation pumping mechanism discussed in detail by Trujillo Bueno & Landi Degl’Innocenti (1997) induces some significant atomic alignment in the lower-levels of the Ca II IR triplet. If lower-level alignment is also present (in addition to upper-level alignment) the radiative transfer equations for Stokes $I$ and $Q$ are (cf. Eqs. [7] and [8] of Trujillo Bueno, 1999):

$$\frac{d}{ds} I = \epsilon_I - \eta_I I - \eta_Q Q,$$

(5)
\[
\frac{d}{ds} Q = \epsilon_Q - \eta_Q \epsilon_I - \eta_I Q, \tag{6}
\]

where the emission coefficients are still given by Eqs.(3)-(4) and

\[
\eta_I = \chi_I \phi_\nu \left[ \rho_0^I(l) + Z \frac{1}{2\sqrt{2}} (3\mu^2 - 1) \rho_0^2(l) \right], \tag{7}
\]

\[
\eta_Q = \chi_Q \phi_\nu \left[ Z \frac{3}{2\sqrt{2}} (\mu^2 - 1) \rho_0^2(l) \right]. \tag{8}
\]

The \(Z\) coefficient depends only on the total angular momentum of the levels involved in each line transition, being equal to -0.565, 0.529 and 0.707 for the 8498 Å, 8542 Å and 8662 Å lines, respectively. According to Eq.(6), although \(\epsilon_Q(8662)\) is zero, linear polarization can be generated through the dichroism term \(-\eta_Q \epsilon_I\), where \(\eta_Q\) is non-zero only if there is atomic alignment in the lower-level of the transition. The relevance of this contribution (due to dichroism) to the emergent fractional linear polarization has been discussed in detail and emphasized by Trujillo Bueno (1999; 2001). In particular, the Eddington-Barbier relation for \(Q/I\) derived in such articles shows clearly that the emergent fractional polarization has two contributions: one coming from the upper-level fractional alignment (which is weighted by \(\mathcal{W}\)), and the other coming from the lower-level fractional alignment (which is weighted by \(Z\)). For the 8662 Å line \(\mathcal{W} = 0\), which implies that the observed \(Q/I\) can only be due to the dichroism contribution, which comes from the atomic polarization of its metastable lower-level (for more details see Trujillo Bueno 2001).

Can we actually explain the observed linear polarization signals through this mechanism? To answer this question we have solved self-consistently the SE and radiative transfer equations (5)-(6) applying the iterative methods outlined by Trujillo Bueno (1999). These radiative transfer methods are the generalization to the Non-LTE problem of the second kind (i.e., to the substantially more complex case in which we have atomic and light polarization instead of simply atomic populations and intensity), of the highly-convergent iterative methods developed previously for the unpolarized case (see Trujillo Bueno & Fabiani Bendicho, 1995).

With respect to the SE equations two points must be noted. First, nine unknowns are now required to describe the excitation state of the Ca II atoms: the populations of the five levels, the alignment of levels 2, 3 and 5, and the \(\rho_0^4\) density-matrix element of the metastable level with \(J = \frac{5}{2}\). Second, extra terms contribute to the rate equations because we are dealing now, in a fully consistent way, with the generation and transfer of atomic polarization in a multilevel atomic system taking into account all the relevant radiation pumping mechanisms.

Fig. 2 shows the variation with optical depth of the fractional atomic alignment \((\rho_0^5/\rho_0^0)\) of levels 2, 3 and 5 of the Ca II in an isothermal atmosphere at 6000 K (note that the alignment of the uppermost level remains unaltered, i.e. as in the previous section case). In this calculation we have also included the role of elastic depolarizing collisions, the corresponding rates estimated following Lamb and ter Haar (1971). The lower-panels of Fig. 3 show the resulting emergent fractional polarization profiles when observing close to the limb of the assumed
model atmosphere ($\mu = 0.1$). We point out that in Fig. 3 and 4 the sign of $Q/I$ has been reversed to follow the sign convention adopted by Stenflo et al. (2000). It can be seen that these profiles reproduce the observed signals quite well (at least qualitatively). In fact, the $Q/I$ of the 8662 Å line is only slightly weaker than the one corresponding to the 8542 Å line, while the $Q/I$ of the 8498 Å line is much smaller. The sign-reversals in the wings of the 8542 Å and 8662 Å lines are due to the change of sign in \( \rho_0^2/\rho_0^0 \) that we have at $\tau \approx 1$ in the isothermal atmosphere we have used (see Fig. 2). As shown in the following section such $Q/I$ wing features disappear when we consider more realistic semi-empirical model atmospheres including temperature gradients and microturbulence.

4. The “realistic” non-magnetic reference case

The upper-panels of Fig. 4 show the emergent fractional linear polarization at $\mu = 0.1$ for the FAL-C solar atmospheric model of Fontela, Avrett & Loeser (1993). The linear polarization amplitudes at the line-core of the 8542 Å and 8662 Å lines are slightly above 0.3% (i.e. almost the same $Q/I$ amplitude we found for an isothermal solar model atmosphere with T=6000 K).

The lower-panels of Fig. 4 show the emergent $Q/I$ signals in a model atmosphere without any chromospheric temperature rise, i.e. in a cool model similar to those proposed by Ayres, Testerman & Brault (1986). In this case the line-core polarization amplitudes are substantially larger. This does not come as a
surprise because the degree of anisotropy of the radiation field is sensitive to the source-function gradient (see Trujillo Bueno 2001; section 3). This sensitivity to the assumed thermal model demonstrates two important points: (1) that the choice of atmospheric model for calculating the non-magnetic reference polarization may imply significant errors in Hanle-effect diagnostics and (2) that we can use the second solar spectrum itself for obtaining clues about the thermal models themselves.

5. Concluding remarks

The observed fractional linear polarization in the Ca II IR triplet cannot be understood without taking properly into account the atomic polarization of the $^2D_{3/2}$ and $^2D_{5/2}$ metastable levels. In particular, the significant linear polarization observed in the 8662 Å line is fully due to dichroism in the solar atmosphere. How can such a metastable-level atomic polarization survive in the highly conductive solar atmospheric plasma? What are the implications of our results for the topology and intensity of the chromospheric magnetic fields? These are certainly challenging questions which we will try to answer in full detail in forthcoming publications (see an advance of the basic ideas in Trujillo Bueno 2001).

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