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Collisional depolarization and transfer rates of spectral lines by atomic hydrogen

II. Application to d states of neutral atoms

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Abstract. The theory of collisional depolarization of spectral lines by atomic hydrogen (Derouich et al. 2003) is extended to d ($l = 2$) atomic levels. Depolarization rates, polarization and population transfer rates are calculated and results are given as a function of the temperature. Cross sections as a function of the effective quantum number for a relative velocity of 10 km s^{-1} are also given together with velocity exponents λ, if they exist, with the assumption that the cross section varies with velocity as $v^{-\lambda}$. A discussion of our results is presented.

Key words. Sun: atmosphere – atomic processes – line: formation – polarization

1. Introduction

In stellar atmospheres, isotropic collisions with the particles of the medium are responsible for a part of the broadening of spectral lines. If a polarizing effect creates an atomic polarization of the lines, they can decrease or even destroy this atomic polarization. Spectral lines observed at the solar limb are linearly polarized by anisotropic scattering of the incident solar radiation. Isotropic collisions with the particles of the medium depolarize the lines. In the solar photosphere and the low chromosphere, depolarizing collisions are dominated by isotropic collisions with hydrogen atoms. When these depolarizing collisions dominate over any other radiative (or collisional) polarizing effects, the atomic levels become depolarized. Therefore depolarization rates, polarization and population transfer rates by collisions with hydrogen are needed in order to interpret the observed polarization.

In Derouich et al. (2003), referred to hereafter as Paper I, a semi-classical theory for depolarization of neutral atomic lines by collisions with atomic hydrogen has been developed and applied to p ($l = 1$) atomic states. This theory is an extension to collisional depolarization of the theory developed in the 1990s by O'Mara and collaborators (Anstee 1992; Anstee & O'Mara 1991, 1995; Anstee et al. 1997; Barklem 1998; Barklem & O'Mara 1997; Barklem et al. 1998) for line broadening by collisions with atomic hydrogen. The present paper is an extension of this theory to d ($l = 2$) atomic levels. In fact, this paper presents the first calculations of the depolarization and the collisional transfer rates for d-atomic states.

A great advantage of the present method is that calculations are not specific for a given perturbed atom. The transition matrix T may be calculated using Coulomb wavefunctions for the valence electron of the perturbed atom and is simply dependent on the effective principal number n^* and the orbital angular momentum quantum number l ($l = 2$ for d-atomic states). Therefore we can calculate depolarization cross sections, polarization and population transfer cross sections for any level of any atom, allowing computation for complex atoms. This is very useful for interpreting the so-called "second solar spectrum" (Stenfo & Keller 1997), where depolarization rates for many levels are needed (Manso Sainzo & Landi Degl'Innocenti 2002).

An extension of our theory to higher l-values, aimed at a more complete interpretation of the second solar spectrum, will be the subject of further papers.

2. Description of the problem and summary of Paper I

In our collision problem, the perturbed atoms collide with a bath of perturbing hydrogen atoms. The hydrogen atom is assumed to remain in its ground state during the collision. The internal states of the perturbed atom are described by the spherical tensor components ${}^{nlJ}\rho_q^k$ of the density matrix. Due to the

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isotropy of the collisions, the depolarization rates, polarization and population transfer rates are q-independent. The contribution of the isotropic collisions to the statistical equilibrium equations is:

$$\left(\frac{\mathrm{d}\,{}^{nlJ}\rho_0^k}{\mathrm{d}t}\right)_{\mathrm{coll}} = -D^k(nlJ,T)\,{}^{nlJ}\rho_0^k + \sum_{J\neq J'} D^k(nlJ\rightarrow nlJ',T)\,{}^{nlJ'}\rho_0^k + \text{quenching term}, \tag{1}$$

where $D^k(nlJ,T)$ is the collisional depolarization rate for the statistical tensor of rank k. Each level of total angular momentum J relaxes with $2J+1$ independent depolarization rates. In particular $D^0(nlJ,T)$ is the destruction rate of population, $D^1(nlJ,T)$ is the destruction rate of orientation (circular atomic polarization) and $D^2(nlJ,T)$ is the destruction rate of alignment which is of interest in the understanding of the second solar spectrum.

We assume that inelastic collisions with hydrogen perturbers do not alter the total population of an atomic level (nlJ). This is the so-called no-quenching approximation. The no-quenching approximation implies that

$$D^0(nlJ,T) = \sum_{J\neq J'} \zeta(nlJ\rightarrow nlJ',T) = 0, \tag{2}$$

where $\zeta(nlJ\rightarrow nlJ',T)(J\neq J')$ is the inelastic collisional rate. The expression for the depolarization rate $D^k(nlJ,T)$ is given in Paper I.

If the quenching must be taken into account, $D^k(nlJ\rightarrow nlJ',T)$ corresponds to collisional transfer of population ($k=0$), orientation ($k=1$) and alignment ($k=2$). $D^k(nlJ\rightarrow nlJ',T)$ can be written as a linear combination of the collisional transition rates between the fine stucture sublevels $\zeta(nlJM_J\rightarrow nlJ'M'_J,T)(J\neq J')$ (Sahal-Bréchot 1977):

$$\begin{aligned} D^k(nlJ\rightarrow nlJ',T) &= (2k+1)\sum_{M_J,M'_J}(-1)^{J+J'-M_J-M'_J} \\ &\quad\times\begin{pmatrix} J & k & J \\ -M_J & 0 & M_J\end{pmatrix}\begin{pmatrix} J' & k & J' \\ -M'_J & 0 & M'_J\end{pmatrix} \\ &\quad\times\zeta(nlJM_J\rightarrow nlJ'M'_J,T). \end{aligned}\tag{3}$$

The expressions between parentheses denote $3j$-coefficients (Messiah 1961).

In particular one obtains

$$D^0(nlJ\rightarrow nlJ',T) = \sqrt{\frac{2J+1}{2J'+1}}\,\zeta(nlJ\rightarrow nlJ',T), \tag{4}$$

where

$$\zeta(nlJ\rightarrow nlJ',T) = \frac{1}{2J+1}\sum_{M_J,M'_J}\zeta(nlJM_J\rightarrow nlJ'M'_J,T), \tag{5}$$

is the collisional transition rate between fine structure levels. $\zeta(\alpha JM_J\rightarrow\alpha JM'_J,T)$ is the collisional transition rate between the sublevels $|\alpha JM_J\rangle\rightarrow|\alpha JM'_J\rangle$. It can be written as a function of the local temperature T and the hydrogen perturber local density n_{H} (Paper I):

$$\begin{aligned}\zeta(\alpha JM_J\rightarrow\alpha JM'_J,T) &= n_{\mathrm{H}}\int_0^\infty\int_0^\infty 2\pi b\,\mathrm{d}b\,v\,f(v)\,\mathrm{d}v \\ &\quad\times|\langle\alpha JM_J|I-S(b,v)|\alpha JM'_J\rangle|^2,\end{aligned}\tag{6}$$

where I is the unit matrix and $T = I - S$ is the so-called transition matrix depending on the impact-parameter b and relative velocity v. Then the collisional depolarization rates and the collisional transfer rates can be expressed in terms of the S-matrix elements for the collision which are functionally dependent on the interaction energy of hydrogen in its ground state with the perturbed atom. The essential difference between various theoretical computations of the depolarization and collisional transfer rates is in the method employed to determine the interaction energy and to determine the S-matrix.

3. Method

Consider a collision between a perturbed atom in a $l=2$ state and hydrogen in its ground state 1s. The perturbed atom is described by an optical electron outside a positively charged core. The effective principal number is given by $n^* = [2(E_\infty - E_{nl})]^{-1/2}$. E_{nl} is the energy of the state of the valence electron and E_∞ is the appropriate series limit for the parent configuration of the perturbed atom state. As in the p atomic levels case (Paper I), depolarizing collisions are due essentially to intermediate-range isotropic interactions between radiating and hydrogen atoms. The so-called Rayleigh-Schrödinger-Unsöld (RSU) interaction potential, used in this work, is of semi-classical nature and is totally electrostatic. For more details we refer to Paper I and to the ABO papers (Anstee 1992; Anstee & O'Mara 1991, 1995; Anstee et al. 1997; Barklem 1998; Barklem & O'Mara 1997; Barklem et al. 1998). We use the notation of Paper I in the following analysis.

Inelastic collisions which leave the radiating atom in a final state ($n'l'$) different from the initial one (nl) are neglected. Thus we consider only the $(2l+1)$ states of the subspace (nl). Since potentials are computed in the rotating frame (Paper I), which is obtained from the fixed laboratory frame by means of the geometrical rotation $R\,(\beta,\frac{\pi}{2},\frac{\pi}{2})$, the interaction potential is diagonal. The $(2l+1)$ RSU potential elements calculated here are (Anstee & O'Mara 1992)

$$\begin{aligned} V_{\mathrm{eff},m_l} &= {}_{(\mathrm{H})}\langle 100|_{(A)}\langle nlm_l|V_{\mathrm{eff}}|nlm_l\rangle_{(A)}|100\rangle_{(\mathrm{H})} \\ &= \langle M_l\big|V\big|M_l\rangle - \frac{1}{E_{\mathrm{p}}}(\langle M_l\big|V\big|M_l\rangle)^2 \\ &\quad+\frac{1}{E_{\mathrm{p}}}\int_0^{+\infty}P^2_{n^*l}I_{l|m_l|}(R,p_2)\mathrm{d}p_2, \end{aligned}\tag{7}$$

in atomic units which are used hereafter. Here $\big|M_l\rangle = |nlm_l\rangle_{(A)}|100\rangle_{(\mathrm{H})}$, $I_{l|m_l|}$ are lengthy complicated analytic functions and $E_{\mathrm{p}} = -4/9$ is adopted. P_{n^*l} is the Coulomb radial wave function for the valence electron of the perturbed atom with quantum defect $\delta = n - n^*$.

The total wavefunction $|\psi\rangle$ of the system (atom+perturber) is taken as the product of the wave function $|\psi\rangle_{(A)}$ of the perturbed atom and that of hydrogen in its ground state $|100\rangle_{(\mathrm{H})}$:

$$|\psi\rangle = |\psi\rangle_{(\mathrm{A})}|100\rangle_{(\mathrm{H})}, \tag{8}$$

and is developed over the basis formed by the products of the separated atoms states $|M_l\rangle$:

$$\left|\psi(t)\right\rangle = \sum_{M_l} a_{M_l}(t)\mathrm{e}^{-\mathrm{i}E^0_{M_l}t}\left|M_l\right\rangle \tag{9}$$

where $E^0_{M_l}$ is the eigenenergy of the system made-up of the two isolated atoms.

The semi-classical coupled linear differential equations are obtained from the time-dependent Schrödinger equation. The transformation from the rotating to the fixed laboratory frame is included following Roueff (1974). For d-states, the coupled differential equations become explicitly (Barklem & O'Mara 1997):

$$\begin{aligned}
\mathrm{i}\frac{\partial a_{-2}(t)}{\partial t} &= \frac{1}{8}a_{-2}(t)(3V_{\mathrm{eff},0} + 4V_{\mathrm{eff},1} + V_{\mathrm{eff},2}) \\
&\quad + \frac{3}{4\sqrt{6}}a_0(t)\mathrm{e}^{-2\mathrm{i}\beta}(-V_{\mathrm{eff},0} + V_{\mathrm{eff},2}) \\
&\quad + \frac{1}{8}a_2(t)\mathrm{e}^{-4\mathrm{i}\beta}(3V_{\mathrm{eff},0} - 4V_{\mathrm{eff},1} + V_{\mathrm{eff},2}) \\
\mathrm{i}\frac{\partial a_{-1}(t)}{\partial t} &= \frac{1}{2}a_{-1}(t)(V_{\mathrm{eff},1} + V_{\mathrm{eff},2}) \\
&\quad + \frac{1}{2}a_1(t)\mathrm{e}^{-2\mathrm{i}\beta}(-V_{\mathrm{eff},1} + V_{\mathrm{eff},2}) \\
\mathrm{i}\frac{\partial a_0(t)}{\partial t} &= \frac{3}{4\sqrt{6}}a_{-2}(t)\mathrm{e}^{2\mathrm{i}\beta}(-V_{\mathrm{eff},0} + V_{\mathrm{eff},2}) \\
&\quad + \frac{3}{4\sqrt{6}}a_2(t)\mathrm{e}^{-2\mathrm{i}\beta}(-V_{\mathrm{eff},0} + V_{\mathrm{eff},2}) \qquad (10) \\
&\quad + \frac{1}{4}a_0(t)(V_{\mathrm{eff},0} + 3V_{\mathrm{eff},2}) \\
\mathrm{i}\frac{\partial a_1(t)}{\partial t} &= \frac{1}{2}a_{-1}(t)\mathrm{e}^{2\mathrm{i}\beta}(-V_{\mathrm{eff},1} + V_{\mathrm{eff},2}) \\
&\quad + \frac{1}{2}a_1(t)(V_{\mathrm{eff},1} + V_{\mathrm{eff},2}) \\
\mathrm{i}\frac{\partial a_2(t)}{\partial t} &= \frac{1}{8}a_{-2}(t)\mathrm{e}^{4\mathrm{i}\beta}(3V_{\mathrm{eff},0} - 4V_{\mathrm{eff},1} + V_{\mathrm{eff},2}) \\
&\quad + \frac{3}{4\sqrt{6}}a_0(t)\mathrm{e}^{2\mathrm{i}\beta}(-V_{\mathrm{eff},0} + V_{\mathrm{eff},2}) \\
&\quad + \frac{1}{8}a_2(t)(3V_{\mathrm{eff},0} + 4V_{\mathrm{eff},1} + V_{\mathrm{eff},2}).
\end{aligned}$$

Having the interaction potential V_{eff}, after integration of these equations, we obtain the transition matrix elements in the $|nlm_l\rangle$ basis for a given velocity and impact parameter. The T-matrix elements in the $|nlJM_J\rangle$ basis, which are needed for the depolarization and collisional transfer rates calculations, are obtained from Eq. (21) of Paper I.

In the irreducible tensorial operator basis, the angular average over all possible directions of the collision plane of the depolarization transition probability is given in Paper I. That of the collisional transfer transition probability is given by:

$$\begin{aligned}
\langle P^k(nlJ \to nlJ', b, v)\rangle_{av} &= \sum_{\mu,\mu',\nu,\nu'} \langle nl\ J\ \mu|T|nl\ J'\ \mu'\rangle \\
&\quad \times\langle nl\ J\ \nu|T|nl\ J'\ \nu'\rangle^* \sum_{\chi}(-1)^{J-J'+\mu-\mu'} \\
&\quad \times\begin{pmatrix} J & J & k \\ \nu & -\mu & \chi \end{pmatrix}\begin{pmatrix} J' & J' & k \\ \nu' & -\mu' & \chi \end{pmatrix}.
\end{aligned} \tag{11}$$

Owing to the selection rules for the $3j$-coefficients, the summation over χ is reduced to a single term, since $\chi = -(\nu' - \mu') = -(\nu - \mu)$.

The depolarization rates $D^k(nlJ, T)$, and the polarization and population transfer rates $D^k(nlJ \to nlJ', T)$ follow from integration over the impact parameters and the velocities with a Maxwellian distribution (for more details see Paper I).

4. Results

In most cases, the behaviour of the cross sections with the relative velocity v obeys a power law of the form:

$$\begin{aligned}
&\sigma^k(nlJ \to nlJ', v)\,(J = J' \text{ and } J \neq J') = \\
&\quad \sigma^k(nlJ \to nlJ', v_0)\left(\frac{v}{v_0}\right)^{-\lambda^k(nlJ \to nlJ')},
\end{aligned} \tag{12}$$

where v_0 is a typical velocity where the cross section is calculated (10 km s^{-1}). In certain cases here, such behaviour was not obeyed (the cross section showed oscillations with velocity).

Table 1 gives the various cross sections as function of n^* for a relative velocity of 10 km s^{-1} and the corresponding velocity exponents $\lambda^k(nlJ \to nlJ')$, if the exponential behaviour was obeyed, are tabulated in Table 2. Then we can obtain the cross sections $\sigma^k(nlJ \to nlJ', v)$ for all velocities from Tables 1 and 2 using Eq. (12). Tables 1 and 2 can be interpolated for an appropriate n^* associated to a given observed line in order to obtain the needed depolarization cross sections and collisional transfer cross-sections. After integration over velocities of these cross-sections, we obtain the depolarization rates and the collisional transfer rates of the line studied.

For cross sections obeying Eq. (12), as in Anstee & O'Mara (1992), the depolarization and the collisional transfer rates can be expressed by:

$$\begin{aligned}
&D^k(nlJ \to nlJ', T)(J = J' \text{ and } J \neq J') = \\
&\left(\frac{4}{\pi}\right)^{\left(\frac{1}{2}\lambda^k(nlJ \to nlJ')\right)} \Gamma\left(2 - \frac{1}{2}\lambda^k(nlJ \to nlJ')\right) \\
&\quad \times v_0\sigma^k(nlJ \to nlJ', v_0)\left(\frac{\overline{v}}{v_0}\right)^{1-\lambda^k(nlJ \to nlJ')}.
\end{aligned} \tag{13}$$

We can generalize this relationship, which is specific to a particular atom owing to its mass, by assuming that $\mu = m_{\mathrm{H}}$ (μ and m_{H} are the reduced and hydrogen mass respectively). This approximation introduces a very small error (Paper I).

As mentioned, in certain cases especially for transfer of linear polarization calculations, the cross sections do not show exponential behaviour with velocity and so λ is not reported

Table 1. Variation of the cross sections, for the relative velocity of 10 km s^{-1}, with the effective principal number. Cross sections are in atomic units.

n^*	$\sigma^2\left(n2\frac{3}{2}\right)$	$\sigma^2(n22)$	$\sigma^2\left(n2\frac{5}{2}\right)$	$\sigma^0\left(n2\frac{3}{2}\rightarrow n2\frac{5}{2}\right)$	$\sigma^2\left(n2\frac{3}{2}\rightarrow n2\frac{5}{2}\right)$
2.5	283	507	342	278	60
2.6	313	566	380	311	65
2.7	351	633	424	351	73
2.8	394	717	477	397	77
2.9	443	808	537	451	87
3	496	900	598	512	104
3.1	553	1008	666	578	116
3.2	628	1109	727	647	139
3.3	711	1210	800	711	163
3.4	812	1348	897	783	179
3.5	905	1470	964	847	190
3.6	1028	1621	1039	920	196
3.7	1108	1763	1106	961	183
3.8	1202	1910	1185	1004	195
3.9	1299	2066	1260	1079	206
4	1294	2191	1367	1117	232

Table 2. Velocity exponents $\lambda^k(nlJ \rightarrow nlJ')(J = J'$ and $J \neq J')$ corresponding to the cross sections of Table 1.

n^*	$\lambda^2\left(n2\frac{3}{2}\right)$	$\lambda^2(n22)$	$\lambda^2\left(n2\frac{5}{2}\right)$	$\lambda^0\left(n2\frac{3}{2}\rightarrow n2\frac{5}{2}\right)$	$\lambda^2\left(n2\frac{3}{2}\rightarrow n2\frac{5}{2}\right)$
2.5	0.207	0.258	0.268	0.259	0.172
2.6	0.223	0.260	0.269	0.258	0.184
2.7	0.222	0.253	0.268	0.259	0.233
2.8	0.200	0.253	0.271	0.257	0.209
2.9	0.214	0.261	0.270	0.253	0.177
3	0.210	0.265	0.280	0.249	0.148
3.1	0.185	0.273	0.282	0.245	-
3.2	0.168	0.274	0.284	0.257	-
3.3	0.153	0.255	0.280	0.267	0.194
3.4	0.137	0.253	0.285	0.279	0.238
3.5	0.140	0.258	0.304	0.286	0.306
3.6	0.131	0.247	0.315	0.272	0.394
3.7	0.175	0.257	0.330	0.249	0.446
3.8	0.179	0.250	0.303	0.234	0.479
3.9	0.208	0.283	0.322	0.237	0.399
4	0.172	0.262	0.296	0.226	0.448

(Table 2). In these cases the linear polarization transfer rates must be computed by a numerical integration over computed cross sections obtained at different velocities.

Figure 1 shows the alignment depolarization rates ($k = 2$) as a function of the local temperature T and n^* for $l = 2$. The population transfer rates ($k = 0$) and the linear polarization transfer rates ($k = 2$) as a function of T and n^* are displayed in Figs. 2 and 3. All these rates increase with the temperature. For a temperature $T \leq 10\,000$ K, the destruction rate of alignment $D^2(n\ 2\ 3/2)/n_{\mathrm{H}} \leq 6 \times 10^{-14}$ rad m^3 s^{-1}, $D^2(n\ 2\ 2)/n_{\mathrm{H}} \leq 8 \times 10^{-14}$ rad m^3 s^{-1} and $D^2(n\ 2\ 5/2)/n_{\mathrm{H}} \leq 5\times10^{-14}$ rad m^3 s^{-1}. The population transfer rate $D^0(n\ 2\ 3/2 \rightarrow n\ 2\ 5/2)/n_{\mathrm{H}} \leq 4 \times 10^{-14}$ rad m^3 s^{-1} and the linear polarization transfer rate $D^2(n\ 2\ 3/2 \rightarrow n\ 2\ 5/2)/n_{\mathrm{H}} \leq 8\times10^{-15}$ rad m^3 s^{-1}. These numerical values are given for $n^* \leq 4$ which include most of the lines of interest for the second solar spectrum studies. The linear polarization transfer rates are smaller than the other rates. In fact Eq. (3) shows that $D^2(n\ 2\ 3/2 \rightarrow n\ 2\ 5/2)$ is a linear combination of $\zeta(nlJM_J \rightarrow nlJ'M'_J, T)$. The coefficients of this linear combination have the sign of $(3M_J^2 - J(J+1)) \times (3M_J'^2 - J'(J'+1))$. Therefore these coefficients are sometimes positive and sometimes negative. Consequently, due to the compensation between the different collisional rates $\zeta(nlJM_J \rightarrow nlJ'M'_J, T)$, $D^2(n\ 2\ 3/2 \rightarrow n\ 2\ 5/2)$ is small compared with the other rates. For similar reasons circular polarization transfer rates ($k = 1$) are negative for ($J = 1/2 \rightarrow J' = 3/2$) and ($J = 3/2 \rightarrow J' = 5/2$). This remark is in agreement with the negative quantum chemistry orientation transfer rate obtained by Kerkeni (2002) for Na D lines ($J = 1/2 \rightarrow J' = 3/2$). We do not give our results concerning the circular polarization transfer because they are not needed for interpretation of the second solar spectrum.

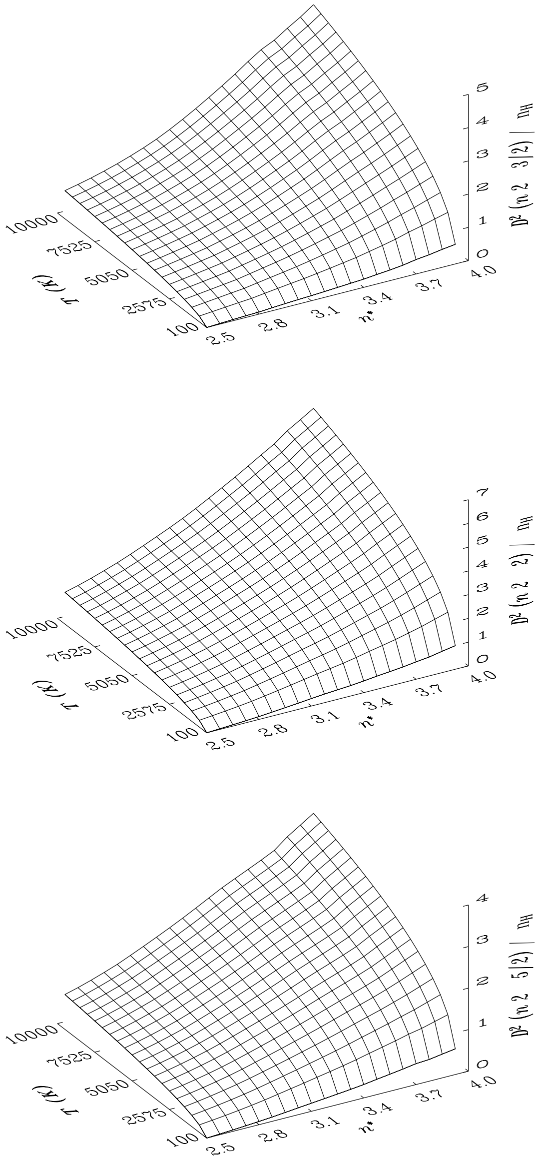

Fig. 1. Depolarization rates ($k = 2$), per unit H-atom density, as functions of temperature T and n^*. For $l = 2$, each figure: $S = \frac{1}{2}$ and $J = \frac{3}{2}$; $S = 0$ and $J = 2$; $S = \frac{1}{2}$ and $J = \frac{5}{2}$. Depolarization rates are given in 10^{-14} rad m^3 s^{-1}.

5. Discussion

The interactions of importance for the depolarization rates, and the polarization and population transfer rates calculations are

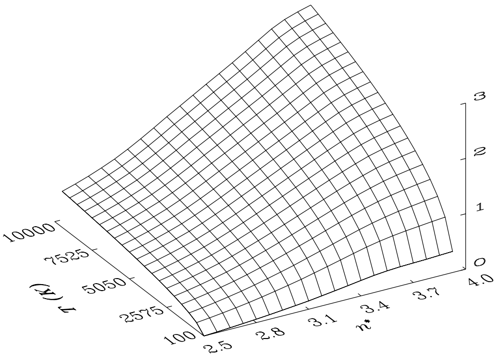

Fig. 2. Population transfer rate ($k = 0$), per unit H-atom density, as a function of temperature T and n^*. $l = 2$, $S = \frac{1}{2}$, $J = \frac{3}{2}$ and $J' = \frac{5}{2}$. Population transfer rate is given in 10^{-14} rad m^3 s^{-1}.

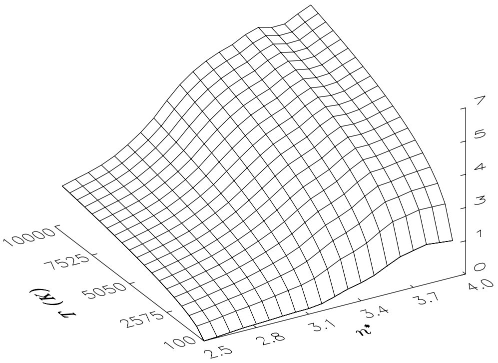

Fig. 3. Linear polarization transfer rate ($k = 2$), per unit H-atom density, as a function of temperature T and n^*. $l = 2$, $S = \frac{1}{2}$, $J = \frac{3}{2}$ and $J' = \frac{5}{2}$. Linear polarization transfer rate is given in 10^{-15} rad m^3 s^{-1}.

the intermediate-range interactions. In the corresponding regions accurate interaction potentials are required. Examination of the RSU potential, used in this work, shows that long-range regions have the usual R^{-6} behaviour but intermediate-regions have $\sim R^{-10}$ behaviour. The van der Waals potential is proportional to R^{-6} at all separations and so that gives a good description of the problem only at long-range separations. The van der Waals potential underestimates the magnitude of the intermediate-range interactions. For this reason it can be seen why the calculations using the van der Waals potential underestimate the depolarization and collisional transfer rates values. The results of Paper I showed that the RSU potential gave depolarization rates which were in agreement (<20% for solar temperatures) with the quantum chemistry calculations.

Unfortunately, there is neither experimental nor quantum chemistry depolarization and collisional transfer rates for d states (at least to the authors' knowledge) to compare with. The main differences between the RSU potentials and those from quantum chemistry, which are more accurate, occur at short-range interactions. We verified that, as for the p states calculations in Paper I, these close collisions do not influence the computed depolarization and collisional transfer rates for the d states. We expect that a rather good agreement with a full quantum mechanical treatment (difference less than 20%) would also occur for our present d states results.

6. Conclusion

The problem is to determine a great number of depolarization and collisional transfer rates by isotropic collisions with H-atoms. Our method was presented, tested and used with success for p states in Paper I. In the present paper we have given depolarization and collisional transfer rates corresponding to d states. These results are needed to model the formation of observed lines, and thus interpret the observations in terms of the solar magnetic field. The need is particularly strong for data for heavy complex atoms which are inaccessible to the quantum chemistry approach. An extension to f atomic states ($l = 3$) is a further interesting step in view of an extrapolation for $l > 3$ states. Such an extension to higher l-values would be useful for a global interpretation of the "second solar spectrum". This work is in progress. Adaptation and application of our theory to the determination of the depolarization and collisional transfer rates of singly ionized atoms lines by collisions with H-atoms will also be the subject of further papers.

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