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Annales Geophysicae

The theoretical impact polarization of the O I 6300 Å red line of Earth aurorae

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Abstract. We are presenting a semi-classical theory of the impact polarization due to a quadrupolar electric excitation, which is the case of this forbidden line. In addition, this line is also radiatively forbidden being a triplet-singlet transition. This last feature is overcome by scaling the semi-classical result to a full quantum calculation at a single energy value. The cross-section and impact polarization are thus obtained as a function of energy, in agreement with the quantum calculations that exist only for the cross-section. The behavior of the impact polarization is found to be quite different than that of the usual dipolar electric interaction. Let us denote as *radial* the polarization parallel to the incident beam or magnetic field, and as *tangential* the perpendicular polarization. In the case of the dipolar electric interaction (permitted lines), the polarization is radial at low energy, and tangential at high energy, and it vanishes at energy about twelve times the threshold energy. In the case of the quadrupolar electric interaction, we observe quite different behavior, with the polarization vanishing point much closer to the threshold energy. This leads us to reanalyze the auroral red line polarization observation by Lilensten et al. (2008). From polarization observations made at Svalbard, they conclude to a rather strong tangential polarization observed during a 4-h recording including two auroral events. The existence of tangential polarization is questioned by our new theory, which leads to reconsidering the contribution of scattered parasitic light from a neighboring city that was mentioned but discarded by the authors. Finally, we conclude that the line is only weakly radially polarized by electron impact, and only during the auroral events. The weak polarization level leads to taking the competing depolarization by collisions with the neighboring O atoms into account, and by the competing isotropical (thus depolarizing) processes for populating the line upper level: the dissociative recombination of O_2^+ colliding with thermal electrons, and above all the reaction $N(^2D)+O_2$. The final diagnostic could be a density determination by depolarization, but it may be rather complicated because it involves several species.

Keywords. Atmospheric composition and structure (Airglow and aurora) – Space plasma physics (Charged particle motion and acceleration; Radiation processes)

1 Introduction

Since the auroral intense red and green lines, which are forbidden lines of neutral Oxygen, are formed by collisional excitation due to electrons coming from the Sun and propagating along the local magnetic field lines, they are prime candidates for displaying impact polarization as a result of their excitation by directed particles. The green line (5577 Å) is however unpolarizable. This is because the total kinetic momentum of the upper level is $2s^22p^4\ {}^1S_0$ is $J=0$, so that this level has only one Zeeman sublevel of momentum $M=0$ and thus, cannot be polarized (because polarization results from a differential Zeeman sublevel population). On the contrary, the red line (6300 Å) may be polarized having as an upper level $2s^22p^4\ {}^1D_2$ with $J=2$, giving five Zeeman sublevels. The lower level of the line is $2s^22p^4\ {}^3P_2$, so that the line is, however, doubly forbidden: first because it occurs inside the fundamental configuration $2s^22p^4$, which prevents the usual dipolar electric character for the transition (which is then dipolar magnetic or quadrupolar electric);

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second because the transition implies a spin flip, the lower level being a triplet $S = 1$ and the upper level a singlet $S = 0$. Thus, the upper level has a long lifetime of 110 s. The excitation threshold is 1.967 eV.

This polarization was searched for unsuccessfully by Bricard and Kastler (1947, 1950) who observed the polarization of the green and red lines of the night sky (the background aurora light) during one month by means of a Lyot type polariscope operating with fringe contrast detection. The polariscope detection threshold was calibrated to be 1.5%, so that the red line polarization was found to be weaker than this threshold.

In the opposite situation of an auroral event, Duncan (1959) detected a 30% linear polarization in an aurora observed at Sydney latitude. The polarization was measured with a rotating polaroïd. The phenomenon was observed at zenith and the polarization direction was found to be oriented perpendicular to the geomagnetic North, i.e. perpendicular to the local magnetic field (see his Fig. 1). This was observed one time over 30 nights of observations.

In the following, we will call radial polarization the one having the radiation electric field aligned with the incident electron average propagation direction, which is also the local magnetic field direction. Tangential polarization is the perpendicular one in analogy with scattering polarization in stellar atmospheres observed at the limb. The polarization observed by Duncan was thus tangential in our definition (see the caption of his Fig. 1). Due to the cylindrical symmetry of the incident electron beam about the propagation or magnetic field direction, rotation of the polarization direction is not expected in the impact polarization observation. The emitted radiation observed perpendicularly to the incident beam is linearly polarized either parallel (radial) or perpendicular (tangential) to the beam, but nothing else. In the following, we will then denote the polarization as a signed quantity: positive for a radial polarization, negative for the tangential polarization, the absolute value being the linear polarization degree.

For interpreting his observation, Duncan (1959) put forward the idea of impact polarization due to directed electrons. He made use of a classical model of the collision. The electron collides with the Oxygen atom with a certain impact parameter. Due to the non-zero impact parameter, the electron skims the Oxygen atom, resulting in a spinning movement of the atom. Considering the collision plane defined by the atom and the incident electron trajectory, there is transfer of a certain amount of kinetic momentum oriented perpendicularly to the collision plane. The emitted radiation magnetic field is parallel to this kinetic momentum, so that the emitted radiation electric field (perpendicular to the magnetic field) is parallel to the electron trajectory. As the observed polarization was, on the contrary, perpendicular to the magnetic field, Duncan concluded that the electron movement was perpendicular to the magnetic field that he had ascribed to the electron gyration about the field. However, Duncan missed the fact that the classical model corresponds to usual dipolar electric permitted emission. Because the Oxygen red line is a dipolar magnetic, the polarization sign has to be reversed accordingly (see for instance Sahal-Bréchot, 1974, Eq. 26). If this had been taken into account, the electron average propagation direction corresponding to Duncan's observations would have been that of the magnetic field one, as expected.

It has to be remarked that this classical model correctly predicts the threshold polarization direction for a permitted line. It predicts the same result as the semi-classical model (classical perturber with trajectory, velocity and impact parameter, and quantum target) of Percival and Seaton (1958): defining the incident electron propagation direction as the quantization axis O_z, the z-component of the incident electron kinetic momentum is zero, and the final electron kinetic momentum is also zero because the outgoing electron velocity vanishes at threshold. Then only $\Delta m = 0$ excitation occurs that leads to π polarization emission (i.e. parallel to the quantization axis which is the electron propagation average direction, which is also the magnetic field direction). This result, valid for a permitted line, has to be sign changed (tangential polarization) for dipolar magnetic emissions like the auroral red line.

Chamberlain (1959), analyzing Duncan's observation, focused on the second reason that makes the red line forbidden: the triplet-singlet transition. He claimed that such a transition can accordingly occur only in collisions implying electron exchange. Such collisions with exchange are effective only for the low energy of the incident electron. Following Chamberlain (1959), low energy electrons would be much more isotropically distributed. Thus, he asserted that only weak polarization could be theoretically justified. He added that depolarizing collisions with the ambient isotropic particles may compete and decrease also the emitted polarization. Besides, he computed the maximum theoretical tangential polarization of this line, taking into account its dipolar magnetic character, and he found Duncan's measurement compatible with this maximum anyway (without modeling the collision itself).

Concerning the collision modeling, one had to wait for the full quantum calculations (see for instance Barklem, 2007, and references therein) where the incident electron spin is taken into account. Applying the rules for kinetic momentum coupling in Quantum Mechanics, it can be seen that the total spin may be conserved even if the atomic spin flips, so that this transition channel remains open in quantum collision codes and this transition remains possible by collision when it is forbidden by radiation. We will analyze this in more detail in the following.

Recently, Lilensten et al. (2006, 2008) undertook reobserving this polarization. They reported a 4-h observation performed at Longyearbyen, Svalbard (78.20° N, 15.83° E geographic, 75.27° N, 111.92° E geomagnetic, Lilensten et al., 2008). Two auroral events occured during that time,

the first one remaining still rather weak. The instrument was pointed towards the magnetic North with an elevation of 15°. Thus, tangential polarization means parallel to the local horizon, whereas radial polarization means parallel to the local vertical, according to our definition. They claimed to have observed a tangential polarization of about 5% between the events which decreased during the events. They ascribed the polarization outside of the event to low energy electron impact due to the permanent polar rain.

The electron energy increases during the events, which would be compatible with the polarization decrease observed at that moment, following the impact polarization theory known at that time where only the case of a permitted line had ben treated. The behavior of the impact polarization as a function of energy has common features between the different elements, as it can be seen in Fig. 4 of Bommier (2006) and in Figs. 1–2 of Lilensten et al. (2006), in which laboratory observations are compared to theoretical models. As expected, the threshold polarization is radial for a permitted line as discussed above. On the contrary, the polarization is tangential at very high energy, where it behaves like radiative scattering polarization. Then, it has to vanish in between and this occurs at the energy about twelve times the threshold energy, regardless of whatever element can be seen in all these figures. Assuming that this remains valid for the O I red line, but changing the sign of the polarization according to the dipolar magnetic character of this line emission, the conclusion of Lilensten et al. (2006, 2008) would be supported with tangential polarization at low incident electron energy that weakens when the energy increases. In the case of the O I red lines, twelve times the threshold energy is 24 eV.

However, this theory was developed for permitted lines, which is not the case of O I 6300 Å. The purpose of the present paper is to present a theory suitable for this line. The incoming electron interacts with the target atom by means of the Coulomb interaction due to its electric field. As explained above, the first non-zero element of this interaction is the quadrupolar electric term. We will present below the cross-section and impact polarization computation for a quadrupolar electric interaction followed by dipolar magnetic emission. We will then develop the calculation in the frame of the semi-classical perturbation model, following Seaton (1962) and Sahal-Bréchot (1969a,b) (see also Sahal-Bréchot et al., 1996; Stauffer and McDowell, 1965, 1966), and the improvement made by Bommier (2006). This improvement consists in taking into account the momentum transfer during the collision. By so doing, the semi-classical theory is enabled for impact polarization.

The result of the new development described in the present paper is that the common feature of vanishing at energy twelve times the threshold energy is completely changed in the case of the quadrupolar interaction. This leads to reanalysis the observations of Lilensten et al. (2008). This is also the object of the present paper, which is organized as follows: Sect. 2 is devoted to model the impact polarization, and Sect. 3 to the reanalysis of the observations of Lilensten et al. (2008).

2 Atomic physics: the theoretical impact polarization

2.1 The O I 6300 Å line: a doubly forbidden line

As stated above, the upper level is $2s^2 2p^4\ {}^1D_2$ and the lower level $2s^2 2p^4\ {}^3P_2$. As both levels belong to the fundamental configuration, the first non-zero term of the electron-atom Coulomb interaction potential is the quadrupolar term. In the general case of a perturber of charge Z_p interacting with an atom (or ion) of charge Z having N electrons, the interaction potential results from the Coulomb interaction

$$V = \frac{Z_\mathrm{p}(Z+N)e^2}{r_\mathrm{p}} - Z_\mathrm{p} e^2 \sum_{i=1}^{N} \frac{1}{r_{ip}}\,, \tag{1}$$

where p refers to the perturber and i refers to the i-th atomic electron. It can be developed in multipolar components, and the restriction to the quadrupolar one (in the case of the long-range approximation, and assuming a single active electron) leads to (case of a neutral atom $Z = 0$)

$$V = -\sum_{\mu=-2}^{+2} \frac{4\pi Z_\mathrm{p} e^2}{5} \frac{r_i^2}{r_\mathrm{p}^3} Y_\mu^2(\hat{r}_\mathrm{p}) Y_\mu^{2*}(\hat{r}_i)\,, \tag{2}$$

where $r_{\mathrm{p},i}$ is the distance of the perturber or atomic electron to the nucleus ($r_{i\mathrm{p}}$ being the distance between the perturber and the atomic electron), and $\hat{r}_{\mathrm{p},i}$ are the two director angles. Y_μ^2 is a spherical harmonic.

This quadrupolar potential corresponds to the interaction between the atom and the incoming electron. As for the radiation emission that follows, the first non-zero contribution comes from the dipolar magnetic interation with the vacuum. Concerning the emitted polarization, the computation is the same as for the usual dipolar electric emission except for the sign that has to be reversed (see for instance Sahal-Bréchot, 1974, Eq. 26).

As previously stated, the second reason that makes this line a forbidden one, is the fact that the transition implies a spin flip from a triplet level to a singlet level.

2.2 Taking into account the triplet-singlet transition

The total system atom+perturber being isolated, the collision occurs within the conservation of the kinetic momentum of the total system. As usual, we neglect the atomic fine structure during the collision, because the collision time is so short that the fine structure energy differences may be neglected within the Heisenberg uncertainty principle. In other words, the spin has no time to rotate during the collision time. Thus, the collision occurs with the separate conservation of the total angular momentum L^T and of the total spin momentum S^T. Considering that the atomic lower level spin is $S = 1$

and the incoming electron spin is $s = 1/2$, two values are possible for S^T in the initial state. They are $S_1^{\mathrm{T}} = 1/2$ and $S_2^{\mathrm{T}} = 3/2$, following the laws for kinetic momentum addition in Quantum Mechanics. Considering now the final state, the atomic upper level has $S = 0$ and the outgoing electron has $s = 1/2$, so that $S_1^{\mathrm{T}} = 1/2$ remains compatible with this final state. Thus, the excitation of the ${}^1D_2$ state from the ${}^3P_2$ one is possible by electron impact, whereas it is forbidden by radiation absorption.

Anticipating the semi-classical development, it can be asserted that this development concerns the angular aspects of the problem depending on the different Zeeman sublevel transitions, whereas the line oscillator strength factorizes. For radiative transitions this oscillator strength is very small because the line is forbidden, which is not the case of the collisional cross-section. In this respect, we scaled our semi-classical result on the result of the quantum calculation at one given energy (here 68 eV for the incoming electron). From Barklem (2007) we received the dimensionless quantity (private communication)

$$\Omega = 1.72 \text{ at } 68 \text{ eV} , \tag{3}$$

which is related to the cross-section Q by

$$\frac{Q}{\pi a_0^2} = \frac{1.72}{5} \times \frac{1}{9} = 0.038222 , \tag{4}$$

a_0 being the Bohr radius. The results of our theory that we present in Fig. 1 below have been scaled to this value at 68 eV, and it can be seen that Fig. 1 top left of Barklem (2007) agrees with our Fig. 1 (bottom) for all energies. 68 eV is not close to the threshold energy 1.967 eV, where the quantum result may be perturbed by sharp resonances.

In the quantum calculation, only the exchange terms contribute to the cross-section of such a triplet-singlet transition. The direct terms vanish. This makes the semi-classical approach particularly difficult.

2.3 Semi-classical formalism for collisional transition in the case of a quadrupolar electric line

The following derivation is the transposition of the one given in Bommier (2006) for the case of the quadrupolar interaction potential. The quantization axis O_z is the incident particle propagation direction.

In the time dependent perturbation theory, the transition probability from the $\alpha = |jm\rangle$ state to $\alpha' = |j'm'\rangle$,

$$P_{\alpha\alpha'}(\rho, \boldsymbol{v}) = \frac{1}{\hbar^2} \left| \int_{-\infty}^{+\infty} V_{\alpha\alpha'} \mathrm{e}^{\mathrm{i}\omega_{\alpha\alpha'} t} dt \right|^2 , \tag{5}$$

is

$$P_{\alpha\alpha'}(\rho, \boldsymbol{v}) = \frac{Z_{\mathrm{p}}^2 e^4}{\hbar^2} \frac{4\pi}{5} a_0^4 \mathcal{Q}(2j+1) \begin{pmatrix} j & 2 & j' \\ -m & -\mu & m' \end{pmatrix}^2 |J_{2\mu}|^2 , \tag{6}$$

where $\mathcal{Q}$ is the factor to be determined by scaling on the single quantum calculation point, and

$$J_{2\mu} = \int_{-\infty}^{+\infty} \frac{1}{r_{\mathrm{p}}^3} Y_\mu^{21}(\hat{r}_{\mathrm{p}}) \mathrm{e}^{\mathrm{i}\omega_{\alpha\alpha'} t} dt \tag{7}$$

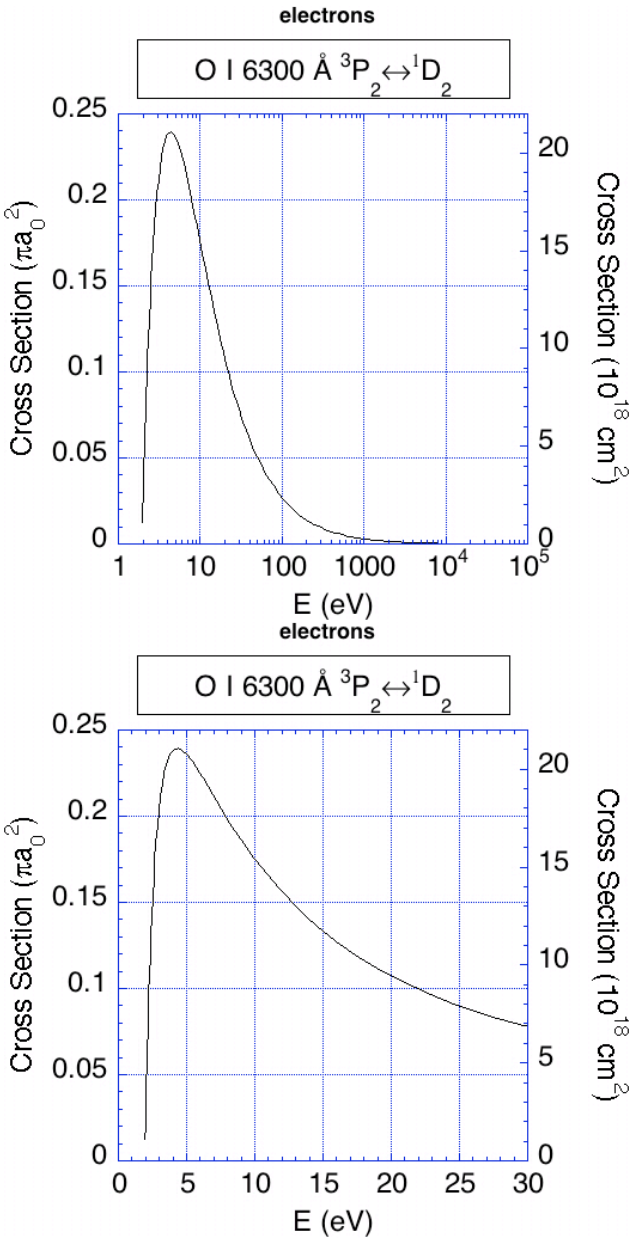

Fig. 1. Cross-section for line collisional excitation by electrons, as a function of the energy of the colliding electron. Bottom: zooming in around the threshold energy, 1.967 eV, for comparison with the quantum calculation result as given in Fig. 1, top left plot, of Barklem (2007).

so that

$$\begin{cases} J_{20} = -\sqrt{\dfrac{5}{4\pi}}\dfrac{1}{v\rho^2}\beta^2 K_0(\beta) \\ J_{2\pm1} = \mp\dfrac{2}{3}\mathrm{i}\sqrt{\dfrac{15}{8\pi}}\dfrac{1}{v\rho^2}\beta^2 K_1(\beta) \\ J_{2\pm2} = \dfrac{2}{3}\sqrt{\dfrac{15}{32\pi}}\dfrac{1}{v\rho^2}\beta^2[K_0(\beta)+\dfrac{2}{\beta}K_1(\beta)] \end{cases} \tag{8}$$

where

$$\beta = \frac{\omega_{\alpha\alpha'}\rho}{v} \tag{9}$$

and $K_{0,1}$ are the modified Bessel functions of order 0,1. The total probability (summed and/or averaged over the magnetic quantum numbers) is in agreement with the calculation of Stauffer and McDowell (1965, 1966).

The transition cross-section is obtained by integration over the impact parameter

$$\sigma(\boldsymbol{v}) = \int_0^\infty P_{\alpha\alpha'}(\rho,\boldsymbol{v})\, 2\pi\rho\, d\rho\,. \tag{10}$$

In the case of permitted lines, a cut-off radius ρ_0 must be introduced because at small ρ, $P_{\alpha\alpha'}(\rho,\boldsymbol{v})$ may become larger than unity and thus unphysical. The cut-off is performed at ρ_0 given by $P_{\alpha\alpha'}(\rho_0,\boldsymbol{v}) = 1/2$ if this ρ_0 is larger than the largest of the two atomic radii for the two states α and α'. Refined values of the probability at the cut-off, based on degeneracy considerations in the case of multiplets, were proposed in the literature (Seaton, 1964; Bernstein et al., 1963; Sahal-Bréchot, 1974). But in the case of a forbidden line $P_{\alpha\alpha'}(\rho,\boldsymbol{v})$ remains largely smaller than unity, and we evaluated the atomic radius ρ_0 value from the single quantum calculated point.

$$\sigma(\boldsymbol{v}) = P_{\alpha\alpha'}(\rho_0,\boldsymbol{v})\pi\rho_0^2 + \int_{\rho_0}^\infty P_{\alpha\alpha'}(\rho,\boldsymbol{v})\, 2\pi\rho\, d\rho\,, \tag{11}$$

leading to

$$\begin{aligned} \sigma_\mu(\boldsymbol{v}) = {} & P_{\alpha\alpha'}(\rho_0,\boldsymbol{v})\pi\rho_0^2 \\ & + \pi a_0^2 Z_\mathrm{p}^2 \left(\frac{\Delta E_{jj'}}{E}\right)^2 \left(\frac{m_\mathrm{p}}{m_\mathrm{e}}\right)^2 \mathcal{Q}(2j+1) \\ & \times \begin{pmatrix} j & 2 & j' \\ -m & -\mu & m' \end{pmatrix}^2 W_\mu A_\mu\,, \end{aligned} \tag{12}$$

where

$$E = \frac{1}{2} m_\mathrm{p} v^2 \tag{13}$$

is the energy of the incident perturber, and

$$\begin{cases} A_0 = \dfrac{1}{4}\beta_0^2\left[K_1^2(\beta_0) - K_0^2(\beta_0)\right] \\ A_{\pm1} = \dfrac{1}{3}[\beta_0 K_1(\beta_0)K_0(\beta_0) \\ \qquad -\dfrac{1}{2}\beta_0^2\left[K_1^2(\beta_0) - K_0^2(\beta_0)\right]\Big] \\ A_{\pm2} = \dfrac{1}{12}\left[2K_1^2(\beta_0)\right. \\ \qquad \left.+\dfrac{1}{2}\beta_0^2\left[K_1^2(\beta_0) - K_0^2(\beta_0)\right]\right] \end{cases}. \tag{14}$$

As in Bommier (2006), the momentum transfer during the collision is taken into account via the W_μ factor

$$\begin{cases} W_0 = 1 \\ W_{\pm1} = W_{\pm2} = 1 - \sqrt{\dfrac{\Delta E_{jj'}}{E}} \end{cases}. \tag{15}$$

This factor is based on classical arguments like those introduced by Duncan (1959), to restrict the transition to the $\Delta m = 0$ components at threshold, following also Percival and Seaton (1958), and to progressively allow the $\Delta m \neq 0$ others when increasing the energy. The factor itself was built on solid angle considerations about the angular momentum transfer. The question in the present work was to extend the factor to the $\Delta m = \pm 2$ case that appears in the quadrupolar interaction. We decided to treat in the same way all the $\Delta m \neq 0$ transitions, whatever the exact Δm value is.

The polarization was then computed by using the irreducible tensors formalism as introduced in Sahal-Bréchot (1977). The cross-section for transition from the k-th order of the j level to the k'-th order of the j' level is then

$$\begin{aligned} Q(jk \to j'k') = {} & \pi a_0^2 Z_\mathrm{p}^2 \left(\frac{\Delta E_{jj'}}{E}\right)^2 \left(\frac{m_\mathrm{p}}{m_\mathrm{e}}\right)^2 \mathcal{Q} \\ & \times (2j+1)\sqrt{(2k+1)(2k'+1)} \\ & \times \sum_K (2K+1) \begin{pmatrix} k & k' & K \\ 0 & 0 & 0 \end{pmatrix} \begin{Bmatrix} j & j & k \\ j' & j' & k' \\ 2 & 2 & K \end{Bmatrix} \\ & \times \sum_\mu (-1)^{k+\mu} \begin{pmatrix} 2 & 2 & K \\ \mu & -\mu & 0 \end{pmatrix} W_\mu A_\mu\,, \end{aligned} \tag{16}$$

which leads to the particular result

$$\begin{aligned} Q(j0 \to j'2) = {} & \pi a_0^2 Z_\mathrm{p}^2 \left(\frac{\Delta E_{jj'}}{E}\right)^2 \left(\frac{m_\mathrm{p}}{m_\mathrm{e}}\right)^2 \mathcal{Q} \\ & \times (-1)^{j+j'}\sqrt{5(2j+1)} \begin{Bmatrix} 2 & 2 & 2 \\ j' & j' & j \end{Bmatrix} \\ & \sum_\mu (-1)^\mu \begin{pmatrix} 2 & 2 & 2 \\ \mu & -\mu & 0 \end{pmatrix} W_\mu A_\mu \end{aligned} \tag{17}$$

for the alignment creation in the upper level. Analogous expressions were used for the transition rate. The polarization

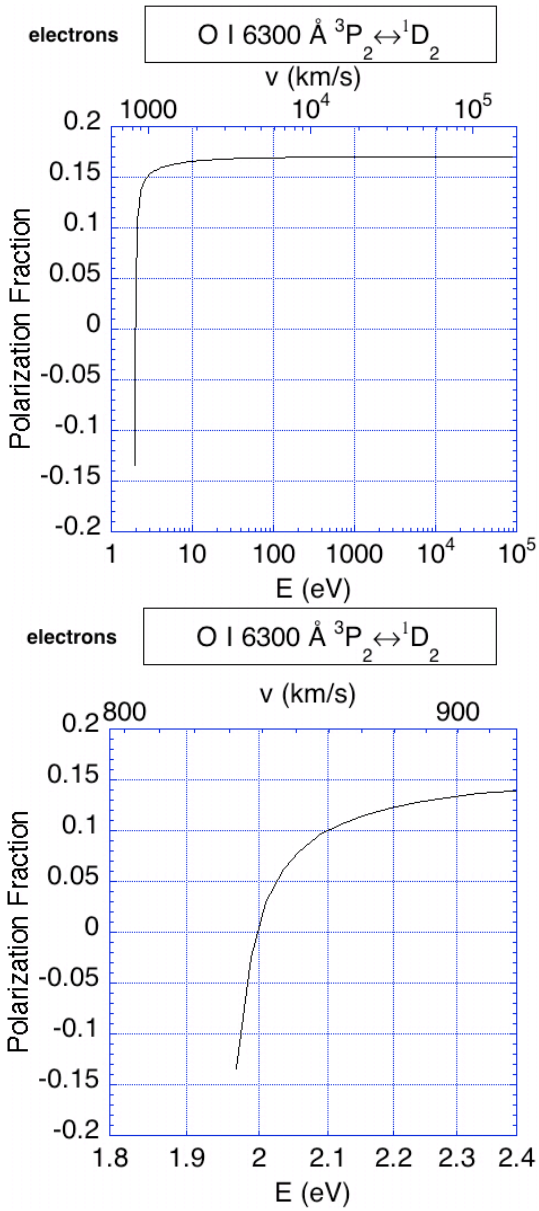

Fig. 2. Impact polarization (linear polarization) due to line collisional excitation by directive electrons, as a function of the energy of the colliding electron, which is assumed to propagate along O_x, the radiation being observed along O_z. A positive polarization means *radial* polarization, i.e. oriented also along O_x, lying inside the scattering plane. A negative polarization means *tangential* polarization, i.e. oriented along O_y, perpendicular to the scattering plane. Bottom: zooming in around the threshold energy, 1.967 eV.

is finally computed following Eqs. (4) and (14) of Sahal-Bréchot (1977), but with $\epsilon = -1$ here because of the dipolar magnetic emission (as in Sahal-Bréchot, 1974, Eq. 26).

The 3-j (in parentheses), 6-j and 9-j (in curly brackets) symbols are projection coefficients of the algebra of angular momenta coupling (see for instance Messiah, 1999). Analytical formulæ for low js are tabulated in Brink and Satchler (1994). Numerical values can be obtained with the "Mathematica" software.

2.4 Computations for O I 6300 Å

2.4.1 The results: the cross-section

The results for the cross-section are given in Fig. 1, where the bottom plot zooms in on the threshold energy. The agreement with the whole plot of Fig. 1 top left of Barklem (2007), to which our result was scaled at one energy point only at 68 eV, demonstrates the validity of our approach. Our results are also in agreement with previous theoretical results by Lan et al. (1972, Fig. 2) and Thomas and Nesbet (1975, Fig. 7). Fairly agreeing experimental results can be seen in Doering and Gulcicek (1989, Fig. 3), where other (also agreeing) experimental results by Shyn and Sharp (1986) are reported.

The semi-classical calculation is much lighter than the full quantum one, and thus the whole collisional cross-section can be obtained for further integration on the velocity distribution, with only one energy point from the quantum calculation.

2.4.2 The results: the impact polarization

The impact polarization is given in Fig. 2 as a function of the incident electron energy. The bottom plot zooms in on the threshold energy. It can be seen that the polarization is tangential at the threshold and radial at high energy, as would be expected for a dipolar magnetic emission, recalling the Introduction. However, the behavior of the polarization between these two extreme cases is very different from the one of a permitted transition. In the case of a permitted transition the polarization vanishes at energy about twelve times the energy threshold as visible in Bommier (2006, Fig. 4) and Lilensten et al. (2006, Figs. 1–2). On the contrary, in the present case of a quadrupolar electric excitation, the vanishing point is found very close to the threshold energy. Considering the definite energy width of any natural velocity distribution, a tangential polarization would not survive after integration over a natural velocity distribution.

This behavior is probably a reflection of angular properties of the polar degree of the interaction potential: vanishing at twelve times the threshold energy for the dipolar interaction (whatever be the element or transition under study), and vanishing very close to the threshold for the quadrupolar interaction. Indeed, we got very similar behavior of the impact polarization during a preliminary step of the present work, when we used the interaction potential proposed by Kazantsev et al. (1999) instead of the quadrupolar term of the Coulomb potential complemented with scaling on quantum calculations at one energy point as we finally did. As a first solution to the problem of the doubly forbidden line, these authors proposed to ascribe the transition to the interaction

of the spins of the atom electrons with the magnetic field produced by the motion of the incident electron (described in a semi-classical model with trajectory and velocity). This interaction is compatible with a triplet-singlet transition. We first did the calculation with this potential and the impact polarization plot was very similar to the present Fig. 2. But the cross-section was so weak that the line would not have been observable. We then abandoned the study of this interaction, but it can be remarked that this interaction although different has also a quadrupolar character, so that we can finally ascribe the behavior of the impact polarization as a function of the electron energy to the polar degree of the interaction.

It can be seen in Fig. 2 that the polarization saturates at 17% at high energy.

3 Auroræ physics: reinterpretation of the observations

3.1 Bricard & Kastler's observation

Bricard and Katsler's observation was a night sky polarization observation, out of an auroral event (Bricard and Kastler, 1947, 1950). In this case the polarization would result from the impact of the polar rain (Lilensten et al., 2008), stemming from the solar wind. The average quiet solar wind velocity being 450 km s^{-1} at Earth, it can be seen in Fig. 2 that this transition implies only the high energy distribution tail, that also rapidly decreases with energy. Thus, integrating the function of Fig. 2 on this distribution would lead to a vanishing global polarization, as observed. Bricard & Katsler's negative result seems fully compatible with our model.

3.2 Duncan's observation

In the light of our Fig. 2, it would not be surprising if a high polarization were observed. If there is a high concentration of very energetic electrons, for instance during an intense event, the 17% saturation level of the polarization could be reached. Duncan (1959) claimed a 30% polarization which could eventually be compatible with our 17%, given all the uncertainties in particular of the measurement. The fact that the 30% polarization was observed one time only over 30 observation nights would also not be surprising, because it would be the sign of a very intense and thus infrequent event. However, the polarization directions fully disagree: Duncan claimed it was tangential, whereas we find it to be radial. For the moment we do not see any explanation.

3.3 Lilensten, Moen, Barthélemy et al.'s observation

As can be seen in Fig. 2 (bottom), integration over a natural velocity distribution having a definite width would hardly lead to a global large tangential polarization as claimed by Lilensten et al. (2008), which leads us to reexamine their observation. As visible in their Fig. 4, bottom, the polarization direction was indeed determined (the noise is not too large), and found to be 75° from the vertical outside of the auroral events. 75° is not 90°, so that this direction is not yet the horizon one. In addition this direction is found to rotate to about 66° from the vertical during the second intense auroral event. We propose the following interpretation: outside of the auroral events, the observed polarization is either of instrumental origin or due to scattered parasitic light. The instrument consisted in a plate rotating in front of a photomultiplier, which may have different responses to the different polarizations transmitted by the rotating plate. This should be calibrated. But the authors do also mention parasitic light coming from an airport and a neighboring city. Scattering this light gives rise to scattering polarization. The observed polarization was not parallel to the horizon, which would be compatible with a city located away from the north-south direction (the detector was pointing north). The auroral event produces radial (vertical) polarization that adds to this parasitic one during the event. Because both polarizations are not perpendicular between themselves, the result of the superposition may appear as a polarization rotation. It is observed that the parasitic polarization is rather high, of the order of 5%. Because the global polarization is only weakly rotated during the events, the auroral polarization has to be weak. Assuming comparable intensity for the city-scattered radiation and the auroral emission, we estimate the auroral polarization to be of the order of 2%, to reproduce the observed polarization rotation. Lilensten et al. (2008) discarded the city radiation from their analysis because they found it incompatible with the fact that they observed variations of the polarization direction. Our new result is that in natural media, only radial polarization can be created in O I 6300 Å by electron impact. We thus propose to reinterpret the polarization curves observed by Lilensten et al. (2008) as follows:

- there was a background parasitic polarization, probably due to city light scattering
- out of the auroral event, there was no auroral polarization (as also observed by Bricard and Kastler, 1947, 1950)
- during the auroral event, the auroral polarization is weak (of the order of 2%) and aligned with the magnetic field (radial)

It can be seen in Fig. 2 that the polarization saturates quickly at 17.0%, so that an energy diagnostic by polarimetry would not be expected. However, the observed polarization is much weaker, of the order of 2%. One is thus led to conclude on the coexistence of depolarizing collisions (already pointed out by Chamberlain, 1959). Elastic collisions with the neighboring O atoms could be good candidates. The auroral polarization measurement could then instead lead to the determination of the density of these O atoms, which is still unknown today. To do this, one has to solve the statistical equilibrium of all the processes. To this purpose, we

need the elastic cross-section (more precisely, the depolarizing cross-section), which is unknown for the moment. Density measurements from depolarization by collisions were already performed in solar prominences (Bommier et al., 1986). However, competing isotropical (thus depolarizing) mechanisms have been proposed by Rusch et al. (1978), Sharp et al. (1979) and Rees and Roble (1986) for populating the line upper level: the dissociative recombination of O_2^+ colliding with thermal electrons, and the reaction $N(^2D)+O_2$, this last process being the dominant one following these authors. The contribution of each of these processes has to be evaluated, and the final density diagnostic by depolarization may be more complicated.

Duncan (1959) and Chamberlain (1959) mention also the Larmor precession of the atomic electron or dipole, which makes a lot of full rotations during the long upper level lifetime. Such a phenomenon occurs also in the forbidden lines of the solar Corona (Sahal-Bréchot, 1974, see Sect. 2). In the general case where the magnetic field is not parallel to the symmetry direction of the anisotropic excitation, this leads to a depolarization of magnetic origin (the magnetic depolarization). But in the present case where the symmetry axis of the incident beam is parallel to the magnetic field, there is no magnetic depolarization because there is cylindrical symmetry about the magnetic field direction, which can be chosen as the quantization axis. Thus, the only depolarizing mechanism to be considered for the O I 6300 Å auroral red line is the depolarization by collisions with the neighboring O atoms, or by the other envisaged upper level populating mechanisms.

4 Conclusion

The agreement between our results (semi-classical) and the ones of Barklem (2007) shows that the behavior of the cross-section and impact polarization as a function of the energy of the incoming electron can be confidently modelled with our approach in which a single energy point is taken from the full quantum calculation. The energy behavior can then be derived from semi-classical considerations in the case of this doubly forbidden line.

We also show that the energy behavior strongly depends on the polar degree of the interaction. The impact polarization changes sign at a certain electron energy point, which is about twelve times the threshold energy for the dipolar interaction, but which is much closer to the threshold for the quadrupolar interaction as is the case for O I 6300 Å.

This has led us to reanalyze the observations by Lilensten et al. (2008), because the previous interpretation was compatible with the old hypothesis of sign change at twelve times the threshold energy. No auroral polarization can be observed outside of the auroral events: the polarization vanishes by integration over the polar rain distribution tail. Their observed polarization at that moment was scattered parasitic light instead. This absence of polarization was also observed by Bricard and Kastler (1947, 1950). During the auroral events, a weak radial polarization of the order of 2% was observed, oriented parallel to the magnetic field direction. This observed polarization is weaker than the theoretical one, leading us to consider the effect of depolarizing collisions with the neighboring O atoms as well. As the impact polarization is found to be insensitive to the energy of the incoming electrons, the energy distribution diagnostic cannot be expected. The density of the neighboring O atoms could be diagnosed instead by depolarization. This requires that the elastic cross-section (more precisely, the depolarizing cross-section) be evaluated, which remains to be done. In addition, one has to take into account the competing isotropical (thus depolarizing) processes for populating the line upper level: the dissociative recombination of O_2^+ colliding with thermal electrons, and the reaction $N(^2D)+O_2$, this last process being the dominant one. The final density diagnostic by depolarization may be more complicated.

High polarization during an auroral event, as observed by Duncan (1959), is also compatible with our model in the case of a very intense event, but the polarization direction observed by Duncan (1959) one time over 30 observation nights remains in disagreement with our model.

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