

# Study of resonance scattering polarization in O I 130 nm lines

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**Abstract.** Here we address the importance of frequency cross-redistribution on the scattering polarization of the O I line at 130.2 nm. We compute the polarized profiles of this line with ordinary partial frequency redistribution and cross-redistribution using a two-dimensional radiative transfer code.

**Keywords.** Scattering, polarization, radiative transfer

## 1. Introduction

The oxygen triplet lines at 130 nm are chromospheric UV lines (see Figure 1 for the grotrian diagram). The intensity spectrum of the triplet has been studied in great detail by Carlsson & Judge (1993), and modeled by Miller-Ricci & Uitenbroek (2002). Scattering polarization and Hanle effect are important chromospheric diagnostic tools. Scattering polarization in the resonance line of O I at 130.2 nm is theoretically investigated recently in Anusha *et al.* (2014). Here we summarize the important results of that paper.

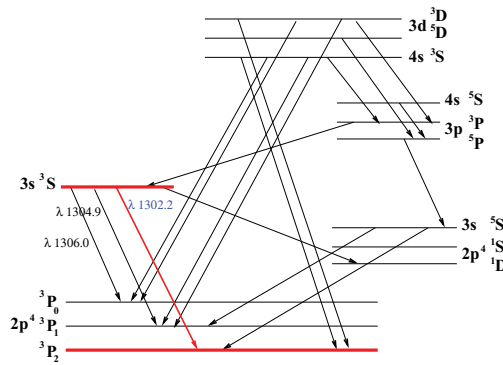
Partial frequency redistribution (PRD) in line scattering means that correlations exist between the frequencies of incident and scattered photons. PRD is represented by two types of functions, namely,  $r_{II}$  and  $r_{III}$  of Hummer (1962). For example, to model scattering polarization in spectral lines such as Ca I 422.7 nm and Ca II K, PRD is necessary. Frequency cross-redistribution (XRD) takes into account the effects of PRD in multi-level atomic systems. XRD is represented by generalized redistribution functions (see e.g., Hubeny 1982, Hubeny *et al.* 1983a,b). For example, O I triplet lines share the same upper level where XRD effects become applicable.

## 2. Theoretical background

In XRD the emission profile is given by (see e.g., Uitenbroek 2001, Miller-Ricci & Uitenbroek 2002)

$$[\psi_{ij}(\lambda, \Omega)]_{XRD} = \phi_{ij}(\lambda, \Omega) \left\{ 1 + \frac{\sum_{k < j} n_k B_{kj}}{n_j P_j} \oint \frac{d\Omega'}{4\pi} \int d\lambda' I(\lambda', \Omega') \right. \\ \left. \times \left[ \frac{R_{kji}(\lambda, \Omega, \lambda', \Omega')}{\phi_{ij}(\lambda, \Omega)} - \phi_{kj}(\lambda', \Omega') \right] \right\}.$$

Here the populations of the  $i, j, k$ -th levels are denoted by  $n_i, n_j, n_k$ , the XRD functions involving the levels  $k, j$  and  $i$  are denoted by  $R_{kji}$ , the Voigt profile function for the line corresponding to transition between levels  $j$  and  $i$  is denoted by  $\phi_{ij}$ , and  $B_{kj}$  or  $B_{ji}$  represent the Einstein-B coefficients for the transitions described by the subscripts  $j$  and



**Figure 1.** Grotrian diagram of the Oxygen I triplet lines. This figure is reproduced from Anusha *et al.* (2014) after correcting here, an error in labeling of 2P<sup>4</sup> <sup>3</sup>P<sub>0</sub> and 2P<sup>4</sup> <sup>3</sup>P<sub>2</sub> energy levels in that paper.

*i.* The sum of collisional and radiative rates is denoted by  $P_j = \sum_{k \neq j} C_{jk} + R_{jk}$ . In the case of ordinary PRD the summation over all subordinate lines in the emission profile coefficient becomes only one term with  $k = i$ .

### 3. Method of solution

We solve the problem in two steps. In the first step, the RH-code (Uitenbroek 2001) solves the multi-level unpolarized radiative transfer equation and the statistical equilibrium equation simultaneously and self consistently. This code is capable of including XRD in the transfer calculations (see Miller-Ricci & Uitenbroek 2002). We use RH-code in the first step to calculate unpolarized intensity profiles, collision and radiative rates, etc., which will be kept fixed in the next step. In second step, two-level atom polarized transfer equation is solved using physical quantities computed in the first step. We solve two-dimensional (2D) polarized transfer equation using two-level atom PRD scattering theory of Domke & Hubeny (1988) and Bommier (1997a,b) respectively for resonance scattering including collisions and the Hanle effect.

The transfer equation is given by

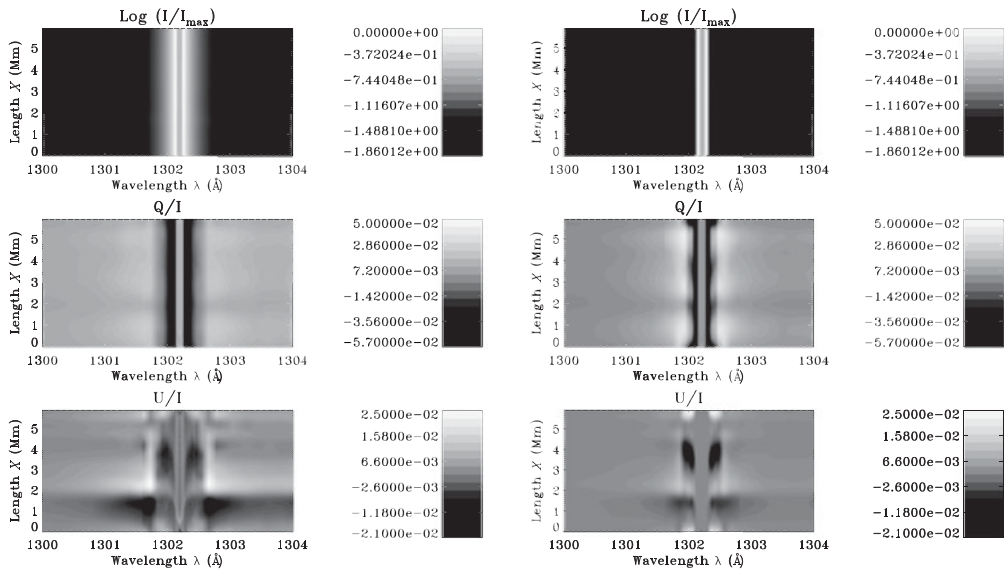
$$-\frac{1}{\kappa_{\text{tot}}(\mathbf{r}, x)} \boldsymbol{\Omega} \cdot \nabla \mathbf{I}(\mathbf{r}, \boldsymbol{\Omega}, x) = [\mathbf{I}(\mathbf{r}, \boldsymbol{\Omega}, x) - \mathbf{S}(\mathbf{r}, \boldsymbol{\Omega}, x)].$$

Here  $\mathbf{I} = (I, Q, U)^T$  is the Stokes vector,  $\mathbf{S}$  is the Stokes Source vector,  $\mathbf{r} = (x, y, z)$  position vector of the ray ( $\boldsymbol{\Omega}$ ),  $\kappa_{\text{tot}}$  is the total opacity and  $x$  is the frequency in reduced units.

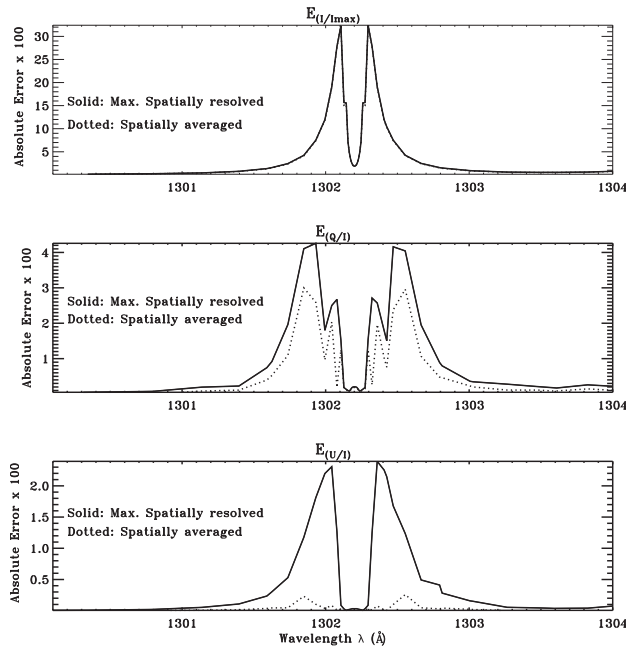
For the radiative transfer calculations we chose an atmosphere which is constructed by combining a 2D snapshot of a 3D magneto-hydro-dynamical simulations of Nordlund & Stein (1991) up to a height of 0.65 Mm and above this height, columns of 1D FALC (see Fontenla *et al.* 1993) atmospheres are used.

### 4. Results

In Figure 2 we show spatial variation of O I line at 130.2 nm for ordinary PRD (left panels) and XRD (right panels). We find that as in intensity profiles (Miller-Ricci & Uitenbroek 2002), ordinary PRD leads to a broadening of the scattering polarization profiles. When frequency coherency in the other lines sharing the same upper level is taken care through XRD, this broadening disappears. 2D transfer effects are shown in the



**Figure 2.** Spatial variation of  $(I/I_c, Q/I_c, U/I_c)$ . Left: PRD profiles; Right: XRD profiles. This figure is reproduced from Anusha *et al.* (2014).



**Figure 3.** Maximum of the absolute difference between ordinary PRD and XRD profiles for spatially averaged and spatially resolved cases.

wings of the O I line at 130.2 nm which are formed in the lower layers of the atmosphere represented by MHD simulations with spatial inhomogeneities.

In Figure 3 we show a comparison of the maximum of the absolute difference between ordinary PRD and XRD profiles for spatially resolved and spatially averaged cases. This figure shows that, intensity profiles are not sensitive to spatial structuring, whereas the

fractional polarization profiles are sensitive to spatial structuring. Therefore the absolute differences of the fractional polarization profiles are larger in the spatially resolved case.

## 5. Conclusions

We have computed the resonance scattering polarization profiles of the O I line at 130.2 nm by solving the 2D polarized radiative transfer equation. We have theoretically investigated the effect of including XRD in unpolarized radiative transfer on the resonance scattering polarization and compared with the polarized profiles computed with ordinary PRD. We find that (1) XRD has a significant effect on the fractional scattering polarization profiles and (2) these profiles are sensitive to the structuring of the atmosphere.

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