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Polarized Line Transfer in the Incomplete Paschen-Back Effect Regime with Angle-dependent Partial Frequency Redistribution

K. N. Nagendra[1,2,*], K. Sowmya[3], M. Sampoorna[1], J. O. Stenflo[2,4], and L. S. Anusha[3]

[1]Indian Institute of Astrophysics, Koramangala, Bengaluru 560 034, India
[2]Istituto Ricerche Solari Locarno, 6605 Locarno-Monti, Switzerland
[3]Max-Planck-Institut für Sonnensystemforschung, Justus-von-Liebig-Weg 3, 37077, Göttingen, Germany
[4]Institute for Particle Physics and Astrophysics, ETH Zurich, CH-8093 Zurich, Switzerland
[*]*Email:* knn@iiap.res.in

Abstract. In the present paper we consider the problem of polarized line formation in the incomplete Paschen-Back effect (PBE) regime taking into account the angle-dependent (AD) partial frequency redistribution (PFR) in scattering. For our numerical studies, we consider an isothermal planar atmosphere and a two-level atom with lower $J_a = 1/2$ and upper $J_b = 3/2$ states and a nuclear spin of $I_s = 3/2$. Such an atomic system is representative of the D_2 line of Na I. For this model atom and model atmosphere, we present a comparison of emergent Stokes profiles computed with AD-PFR and the numerically simpler approximation of angle-averaged (AA) PFR matrices.

1 Introduction

Scattering of the solar limb-darkened radiation field by atoms produces linearly polarized spectrum of the Sun (namely, the second solar spectrum; see Stenflo 1994). This spectrum is modified in the presence of arbitrary strength magnetic fields through the Hanle, Zeeman, and Paschen-Back effects. Also, PFR plays a fundamental role in shaping the inner wings of linearly polarized profiles of strong resonance lines. Polarized line formation in arbitrary strength fields including scattering on a two-level atom with hyperfine structure splitting (HFS), PBE, and AA-PFR was considered in Sampoorna et al. (2019a,b). For the same problem, here we present the effects of the AD-PFR on resonance polarization of spectral lines formed in the incomplete PBE regime. We recall that, in the incomplete PBE regime the magnetic splitting is comparable to or larger than the HFS.

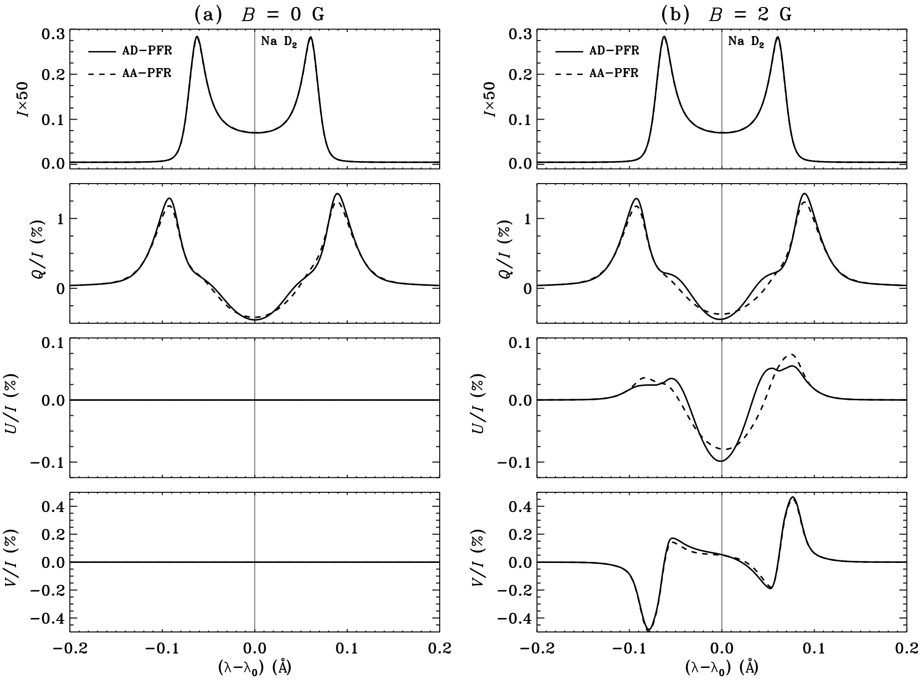

Figure 1. Comparison of emergent Stokes profiles of theoretical Na I D_2 line, computed using AD-PFR (solid lines) and AA-PFR (dashed lines) matrices. The line-of-sight is at ($\mu = 0.11$, $\varphi = 0°$). A self-emitting isothermal slab with model parameters (T, $\Delta\lambda_{\rm D}$, ϵ, r) = (100, 25 mÅ, 10^{-4}, 10^{-7}) is considered. The magnetic field orientation $(\vartheta_B, \varphi_B) = (90°, 45°)$. Panel (a) corresponds to $B = 0\,$G, and panel (b) to $B = 2\,$G.

2 The atomic and atmospheric models

For details on the basic equations and the numerical method of solution for the problem at hand the reader may refer to Sampoorna et al. (2019a, see also Sowmya et al. 2014). We consider an atomic system representative of the D_2 line of Na I. The D_2 line results from a $J_b = 3/2 \rightarrow J_a = 1/2$ transition. The line center wavelength (λ_0) corresponding to this transition is 5889.95095 Å. The nuclear spin $I_s = 3/2$. The hyperfine structure constants corresponding to the lower and upper levels are given by $\mathcal{A}_{1/2} = 885.81\,$MHz, $\mathcal{B}_{1/2} = 0$, $\mathcal{A}_{3/2} = 18.534\,$MHz, and $\mathcal{B}_{3/2} = 2.724\,$MHz (see Steck 2003). The Einstein A_{ba} coefficient is $6.3 \times 10^7\ {\rm s}^{-1}$.

An isothermal planar model atmosphere is characterized by $(T, \Delta\lambda_{\rm D}, \epsilon, r)$, where T is the total line integrated vertical optical thickness of the medium, $\Delta\lambda_{\rm D}$ is the Doppler width, ϵ is the thermalization parameter, and r is the ratio of continuum to line integrated opacity. We consider a self-emitting slab with parameters $T = 100$, $\Delta\lambda_{\rm D} = 25\,$mÅ, $\epsilon = 10^{-4}$, and $r = 10^{-7}$. The effects of elastic collisions are neglected. The line-of-sight is chosen as ($\mu = 0.11$, $\varphi = 0°$), where $\mu = \cos\vartheta$ with ϑ the co-latitude and φ is the azimuth of the radiation field with respect to the atmospheric normal. The positive Stokes Q direction is

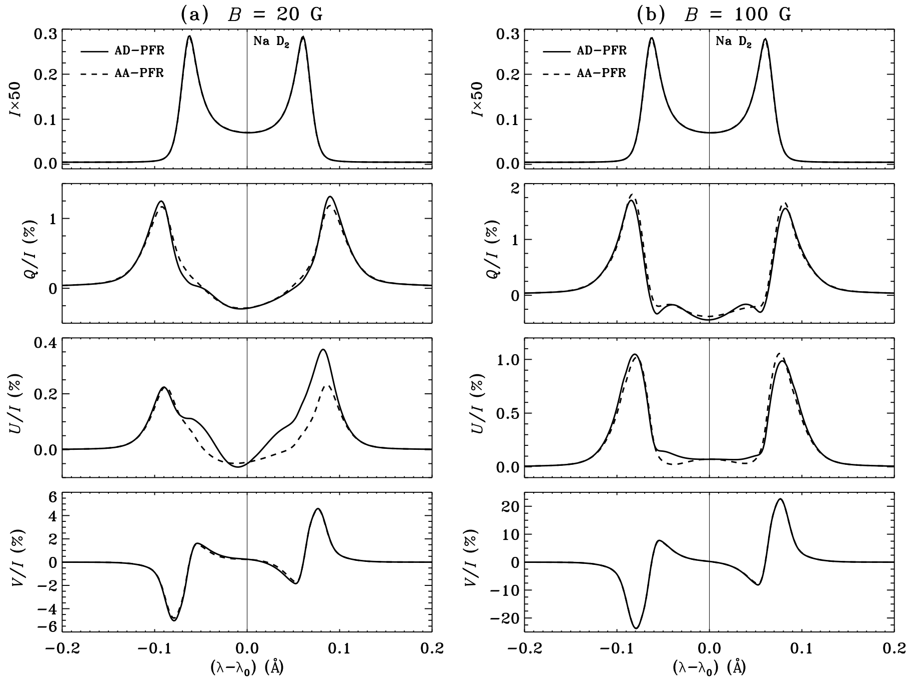

Figure 2. Same as Figure 1, but for $B = 20\,\mathrm{G}$ in panel (a) and $B = 100\,\mathrm{G}$ in panel (b).

chosen to be perpendicular to the limb.

3 Numerical results

In Figures 1 and 2 we compare the emergent I, Q/I, U/I, and V/I profiles computed using the AD-PFR and AA-PFR matrices for different magnetic field strength values. In the absence of magnetic fields, the emergent I and Q/I profiles computed with AD-PFR and AA-PFR do not differ greatly (compare solid and dashed lines in Figure 1a). This result is in agreement with those obtained by Supriya et al. (2013), who present the effects of AD-PFR on the non-magnetic resonance polarization profiles in the cases of a two-term atom without HFS (including J-state interference) and a two-level atom with HFS (including F-state interference). In the presence of magnetic fields, differences are significant particularly in the U/I profiles. This is expected, as the Stokes U is generated by the breaking of axisymmetry of the problem. These results are in agreement with the conclusions of Nagendra et al. (2002), Nagendra & Sampoorna (2011), and Sampoorna et al. (2017), where they consider the case of a two-level atom without HFS. The V/I profiles are relatively insensitive to the choice of the redistribution matrix (namely, AA or AD). Our numerical studies show that, for $B > 30\,\mathrm{G}$ the differences between emergent Stokes profiles computed with AD-PFR and AA-PFR decrease (for e.g., compare solid and dashed lines in Figure 2b) and nearly vanish for $B \geqslant 200\,\mathrm{G}$.

4 Conclusions

In the present paper we solve the polarized line transfer equation in the incomplete PBE regime including AD-PFR. For computational simplicity, we consider a self-emitting isothermal slab of moderate optical thickness T. We present a comparison of emergent Stokes profiles of theoretical Na I D_2 line for few values of field strength in the incomplete PBE regime. AA-PFR can safely be used to compute the non-magnetic (I, Q/I) profiles. AD-PFR effects are significant in the (Q/I, U/I) profiles, in the presence of non-zero magnetic fields. The U/I profiles show a higher sensitivity to AD-PFR than the Q/I profiles. The V/I profiles are marginally affected by AD-PFR effects. For the theoretical model line and the model atmosphere considered in the present paper, the AD-PFR effects are significant for fields up to 30 G.

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