2D Radiative Transfer Simulations with Angle-Dependent PRD

A. B. Gorshkov

Sternberg Astronomical Institute, 119899 Moscow, Russia

P. Heinzel

Astronomical Institute, 25165 Ondřejov, Czech Republic

Abstract. We demonstrate how the angle-dependent redistribution function can be incorporated into the 2D transfer modelling of solar prominences. Some preliminary numerical simulations have been performed and we present their results by comparing the emergent hydrogen $L\alpha$ line profiles computed with the angle-averaged and angle-dependent redistributions.

1. Introduction

Standard angle-averaged redistributions are currently used for Lyman lines in prominences and prominence-like structures, both in 1D (Gouttebroze et al., 1993; Heinzel, 1995), as well as in 2D cases (Paletou, 1995). Since 2D transfer computations can explicitly account for strong anisotropies of the incident solar radiation, the angle-dependent approach seems to be more appropriate in such cases. In the present contribution we investigate this problem and demonstrate the differences between angle-averaged and more rigorous angle-dependent 2D simulations for the case of prominences.

To achieve this, we have applied a 2D code of Gorshkov (1996) to the problem of radiative transfer in solar prominences (Fig. 1) for the case of 4-level plus continuum HI atom. The main features of the code are: Multilevel Accelerated Lambda Iterations (MALI) scheme with Partial Frequency Redistribution (PRD) in resonance lines; modified long-characteristics method (timing is linearly proportional to the number of grid points) for 2D solution of Radiative Transfer Equation (RTE); an ability to calculate angle- and height-dependent boundary conditions based on observational data.

2. Basic Formulae

2.1. Angle-Dependent PRD

In our calculations we used the redistribution function in the form:

$$R(\nu', \nu, \Theta) = \gamma R_{II}(\nu', \nu, \Theta) + (1-\gamma)\phi(\nu)\phi(\nu'),$$

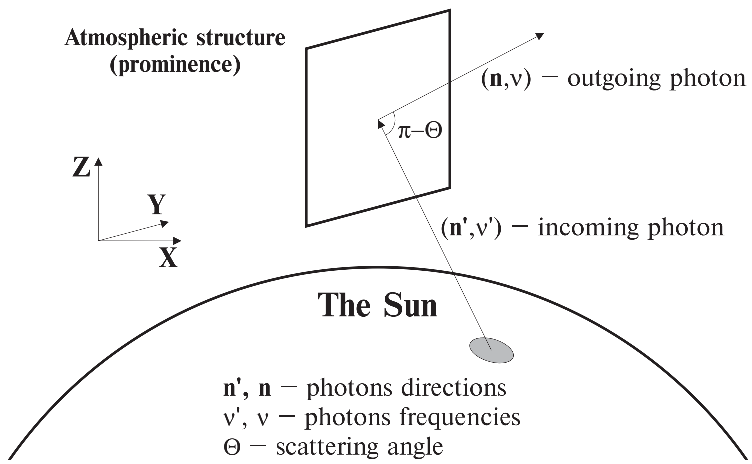

Figure 1. Photon scattering geometry

where γ is the coherence parameter, Θ is the scattering angle between directions of the incoming and the outgoing photons ($\mathbf{n}'$ and $\mathbf{n}$, correspondingly), and R_{II} represents Hummer's (1962) function for the case of purely coherent scattering in the atom's frame.

Similarly to the angle-averaged case, PRD effects are taken into account by introducing the ratio of emission and absorption coefficients for a given line transition ij $(i < j)$:

$$\rho_{\nu\mathbf{n}} \equiv \frac{\psi_{\nu\mathbf{n}}}{\phi_\nu} = 1 + \gamma \frac{n_i}{n_j} \frac{B_{ij}}{P_j} (\bar{R}_{II}(\nu, \mathbf{n}) - \bar{J}),$$

where n_i and n_j are the populations of atomic levels i and j, B_{ij} is the Einstein coefficient for absorption, P_j represents a probability for an atom to leave the level j; $\bar{J} = (4\pi)^{-1} \int_0^\infty \int_0^{4\pi} I_{\nu'\mathbf{n}'} \phi_{\nu'}\, d\nu'\, d\Omega'$ is the mean integrated intensity and $\bar{R}_{II}$ stands for the scattering integral (see Hubený, 1985). Contrary to the *standard* PRD, ρ now depends on the angle Θ because $\bar{R}_{II}$ has the following form:

$$\bar{R}_{II}(\nu, \mathbf{n}) = (4\pi\phi_\nu)^{-1} \int_0^\infty \int_0^{4\pi} R_{II}(\nu', \nu, \Theta) I_{\nu'\mathbf{n}'}\, d\nu'\, d\Omega', \qquad (*)$$

where the redistribution function is (x, x' are frequencies counted from the line center and expressed in Doppler units):

$$R_{II}(x', x, \Theta) = \begin{cases} \frac{g(\Theta)}{\pi \sin\Theta} \exp\{-[\frac{1}{2}(x - x')]^2 \csc^2 \frac{\Theta}{2}\} H[a \sec\frac{\Theta}{2}, \frac{1}{2}(x + x') \sec\frac{\Theta}{2}] & 0 < \Theta < \pi \\ \frac{1}{\sqrt{\pi}} H(a, x')\delta(x - x') & \Theta = 0 \\ \frac{a}{2\pi^{3/2}} exp\left\{-(\frac{x-x'}{2})^2\right\} \left[(\frac{x+x'}{2})^2 + a^2\right]^{-1} & \Theta = \pi \end{cases}$$

Here $H(a,x)$ is the Voigt function and a the damping parameter. Examples of the function $R_{II}(x',x,\Theta)$ are shown in Fig. 2. Since the function varies very sharply with Θ and x', we used appropriate Θ- and x'-dependent frequency quadratures for the evaluation of the scattering integral (*).

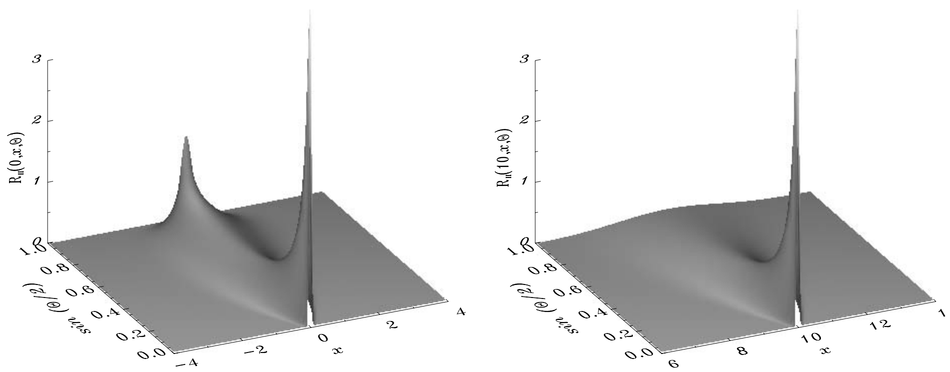

Figure 2. Function $R_{II}(x',x,\Theta)$ for $x'=0$ (left) and $x'=10$ (right)

2.2. Changes in the Formal Solution of RTE

Since we need to know specific intensities I_ν to calculate the integral (*), the following changes in a standard Feautrier scheme of the formal solution of RTE are necessary:

$$\begin{aligned} d^2u/d\tau^2 &= u - \bar{S} + d\Delta S/d\tau, \\ d^2v/d\tau^2 &= v - \Delta S + d\bar{S}/d\tau \end{aligned}$$

Here $u=(I_\nu^+ + I_{-\nu}^-)/2$ and $v=(I_\nu^+ - I_{-\nu}^-)/2$ are Feautrier variables; $\bar{S}=(S_\nu^+ + S_{-\nu}^-)/2$ and $\Delta S=(S_\nu^+ - S_{-\nu}^-)/2$ represent averaged sum and difference of source functions in positive (+) and negative (−) directions. The scale of optical depths τ is calculated in a positive direction. To solve these transfer equations, we introduced corresponding changes in an improved Feautrier method of Rybicki and Hummer (1991).

3. Results and Conclusion

Using the above-described approach, we have computed 2D transfer for the prominence model having the following parameters: dimensions $\Delta Z = 2\,000\,\mathrm{km}$, $\Delta Y = 2\,000\,\mathrm{km}$, low boundary at the height $H = 10\,000\,\mathrm{km}$ above the solar surface, temperature $T = 8\,000\,\mathrm{K}$, gas pressure $P_{gas} = 0.05\,\mathrm{dyn/cm^2}$, turbulent velocity $V_{turb} = 5\,\mathrm{km/s}$. Angle-dependent incident radiation field was used similarly as in Gorshkov (1996), where other details of our numerical procedure are described. As a result of preliminary simulations, we present a comparison of emergent $L\alpha$ line profiles (taken in the center of the slab) for the cases of angle-averaged and angle-dependent PRD (see Fig. 3). Main effect seen here is a lowering of intensity in the line core. As a next step in this work we intend to

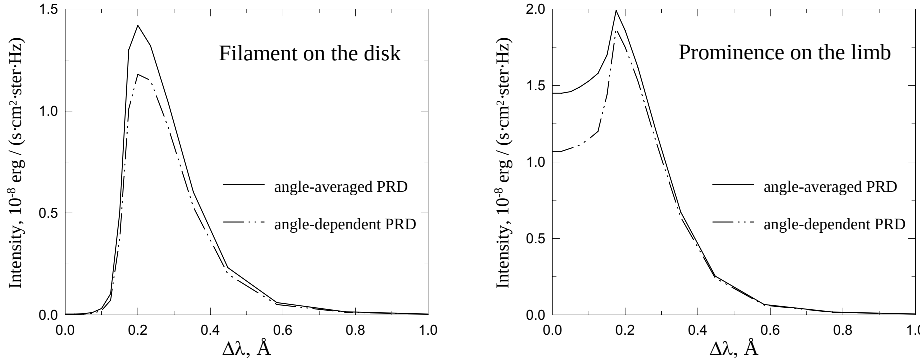

Figure 3. Calculated emergent profiles for $L\alpha$ line as seen on the disk (left) and on the limb (right)

demonstrate the influence of the angle-dependent PRD on spectral diagnostics of prominence plasmas.

Acknowledgments. A.B.G. highly appreciates the support from the colloquium organizers which enabled him to attend the meeting. Travel expenses were covered from the grant GACR 1199.

References

Gorshkov, A. B. 1996, in N. Mein and S. Sahal-Brechot (eds.), Science with THEMIS, Proc. Forum THEMIS, Observatoire de Paris-Meudon, p. 273

Gouttebroze, P., Heinzel, P., & Vial, J.-C. 1993, A&AS, 99, 513

Heinzel, P. 1995, A&A, 299, 563

Hubený, I. 1985, Bull. Astron. Inst. Czechosl., 36, 1

Hummer, D. G. 1962, MNRAS, 125, 21

Paletou, F. 1995, A&A, 302, 587

Rybicki, G. B., & Hummer, D. G. 1991, A&A, 245, 171