MULTIDIMENSIONAL RADIATION TRANSFER IN THE INHOMOGENEOUS STELLAR ATMOSPHERES

M. I. Stodilka

Astronomical Observatory, Ivan Franko National University of Lviv, Lviv, Ukraine
e-mail: sun@astro.franko.lviv.ua

We solved 2D non-equilibrium radiation transfer problem for different atmosphere models. 2D NLTE radiation transfer problem is solved by using multigrid techniques. On the each grid the solution is found by the accelerated Λ–iteration method. For the formal solution of the radiation transfer problem the short characteristics method is used; we also used the linear convergence improvement procedure. The solution convergence is fast for all the atmosphere models that were tested. We considered influence of NLTE effects on the Fe I equivalent width spatial variations over granular intergranular layers in the solar atmosphere.

PROBLEM DEFINITION

Stellar atmosphere is a totality of different nonuniformities (granulation, spots, *etc.*), therefore, it is impossible to describe radiation transfer in the limits of the one dimensional model. The problem may be solved by the differential methods. But these methods are not well in the case of the model atom with a great number of levels. In such cases the iterative methods are to be used that deal with an approximate operator, but give exact solutions. Our approach is based on the complex method elaborated by Bueno and Auer for multilevel 3D problem [1].

Let us consider 2D plane parallel model of the atmosphere. All the parameters are given in the knots of 2D grid. Using the radiation transfer equation provided a known source function one can find after some algebra relationship between intensities at different points of the atmosphere:

$$I_\nu = I_{\nu 0}\mathrm{exp}(-\Delta\tau_\nu) + S_\nu(1 - \mathrm{exp}(-\Delta\tau_\nu)) + \Delta S_\nu/\Delta\tau_\nu * (1 - (\Delta\tau_\nu + 1)\mathrm{exp}(-\Delta\tau_\nu)), \tag{1}$$

where $I_{\nu 0}$ is the initial intensity, $\Delta\tau_\nu$ is the optical depth between these points, S_ν is the source function.

The radiation transfer equation connects intensity with level populations $\mathbf{n}$ which satisfy statistical equilibrium equations. The equations may be written in a matrix form:

$$\mathbf{An} = \mathbf{b}. \tag{2}$$

Matrix $\mathbf{A}$ is generated by radiative and collisional transitions. All the elements of the vector $\mathbf{b}$ with the exception of the last are equal to zero. Then the solution of both equations is:

$$J_\nu = \Lambda_\nu S_\nu, \tag{3}$$

J_ν is an averaged intensity. It is a simple Λ–iteration procedure. Its convergence is slow. To improve convergence we shall represent Λ–operator as a sum of explicit and approximate operators. In a latter operator representation the line core photons leave the transfer and the solution convergence is faster. It is an accelerated Λ–iteration. Then for the intensity we obtain:

$$J_\nu^{(n)} = J_\nu^{(n-1/2)} + a_\nu S_\nu^{(n)} - a_\nu S_\nu^{(n-1)}, \tag{4}$$

where n is a number of iterations; $J_\nu^{(n-1/2)} = \Lambda_\nu S_\nu^{(n-1)}$; a_ν are the coefficients, obtained from Equation (1). For the multilevel problem Equations (4) are inserted into Equations (2). The system of equations becomes linear:

$$\mathbf{A}^*\mathbf{n} = \mathbf{b}. \tag{5}$$

Equations (5) are preconditioned. The iteration procedure convergence is linear; calculations require many iterations. Number of iterations is much less when the acceleration procedure is used. We used Ng acceleration.

The radiation transfer problem is solved by using multigrid techniques. This approach guarantees the convergence to the true solution since long periodical oscillations of the solution are filtered and the convergence becomes essentially improved. The solution on each grid is found by the accelerated Λ–iteration. For the formal solution of the radiation transfer equation the short characteristics method is used; we also used the linear convergence improvement procedure.

RESULTS

We tested our program using different plane-parallel atmosphere models: a) uniform solar models: HSRA, VAL; b) Maltby solar spot model, which corresponds spectral class K0 star; c) nonuniform: quasistationary single scale and non-stationary multiscale solar granulation models. As these comprehensive tests showed the convergence of the solution is fast enough and the described techniques allow to study inhomogeneous astrophysical plasma.

In this paper we present some results of the Fe I lines spatial variations calculations for non-stationary solar granulation [2] using the above mentioned techniques. The Fe I lines calculation is made for 21-level model of the atom, which consists of 18 Fe I levels, two Fe II lower levels and the ground Fe III level. We took into account doppler shifts of the absorbtion coefficient profiles along ray propagation, so profiles are asymmetric and spread by nonthermal velocities.

We shall consider results just only for one weak line λ 671.032 nm. For the line the largest discrepancy between LTE and NLTE equivalent widths exists. The line has a small EPL and is formed in the deep atmosphere layers. In Figs. 1a, 1b we show dependence of equivalent widths (NLTE and LTE) from continuum intensity (normalized by its middle value) for 19 minutes sequence of 38 models; a spatial smearing is not accounted. As we see, in the granular NLTE effects (due to photoionizations and bound-bound transitions) sufficiently

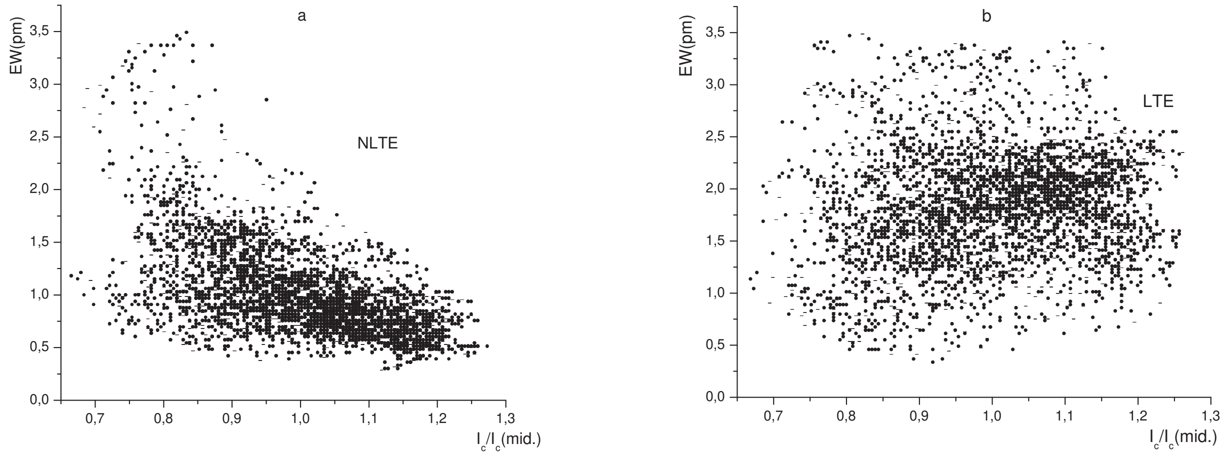

Figure 1: Dependence of equivalent widths from intensity for λ 671.032 nm Fe I

decrease equivalent widths. In the region of low continuum intensity the equivalent width variability increases, that's because of line spread by descending flows and adiabatic gas rarefication. In the LTE conditions the Fe I equivalent widths get stronger in the granular and are weaker in the intergranular regions, while in the more realistic nonequilibrium conditions that dependence has a small negative slope. The upper cooler layers over bright granular regions are more ionized by UV radiation than the hotter intergranular layers, so Fe I levels are more depleted in the granular, lines are formed deeper and have smaller equivalent widths. NLTE effects smooth spatial fluctuations of equivalent widths. In Fig. 1a one can see separation of the dependence into two branches in the intergranular region. Such a separation is determined by the overdone interaction of descending flows in 2D models. The other lines show the similar dependences.

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