A READY-MADE CODE FOR THE COMPUTATION OF PROMINENCE NLTE MODELS

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Abstract. A computer code is proposed for the computation of simple NLTE models of solar prominences. These models consist of plane-parallel slabs, with constant pressure and temperature, standing vertically above the solar surface. Each model is defined by five parameters: temperature, density, geometrical thickness, microturbulent velocity and height above the solar surface. The code computes the electron density, hydrogen level populations inside the slab, and determines the line profiles and continua emitted by the slab. An example of application of this code is given.

1. Introduction

The determination of physical conditions in solar prominences from spectral observations is not straightforward, since the plasma in these objects is far from local thermodynamic equilibrium. So, this diagnostic requires the use of non-LTE modelling. From 1974 to 1983, Heasley and co-workers studied models of solar prominences formed of plane-parallel slabs with constant temperature (or variable temperature determined by energy balance), standing vertically above the solar surface, and irradiated on both faces (see Heasley and Milkey, 1983, and references therein). This kind of modelling was pursued by Heinzel, Gouttebroze, and Vial (1987), who introduced detailed incident radiations deduced from observations of the solar surface, and studied the emitted hydrogen spectrum resulting from partial redistribution processes in Lyman lines. Later on, Gouttebroze, Heinzel, and Vial (1993, hereafter GHV) computed and tabulated hydrogen lines and Lyman continuum for a set of 140 plane-parallel models of different temperature, pressure and thickness. Other parameters were fixed to constant (and somewhat arbitrary) values. In particular, the microturbulent velocity was set to 5 km s^{-1} and the altitude to 10 000 km above the solar surface. The number of tabulated models was restricted for practical reasons, but it was obvious that this table could not contain all the combinations of parameters that are necessary for the diagnosis of observations.

In the meantime, the computer hardware was considerably improved. The calculations of GHV were performed on a large computer (Cray-2). Today, similar codes are running on personal computers. So, we decided to propose a revised version of the code used by GHV, allowing every user to compute the prominence mod-

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els corresponding to his personal needs. This code, named PROM4, is presented below.

2. Numerical Methods

The principle of computation is the same as that of the code used in GHV. The radiative transfer equations in the lines and continua of hydrogen are solved by a finite-difference method (Feautrier, 1964) with variable Eddington factors (Auer and Mihalas, 1970). The other equations, namely that of statistical equilibrium of level populations, ionization and pressure equilibria, are solved by iteration. This is basically an 'equivalent-two-level-atom' method, as that described by Cuny (1967) or Avrett and Loeser (1987).

At the beginning, the intensities inside the slab are set by assuming that the medium is optically thin in all transitions. With these intensities, we compute the radiative transition rates. We start from an arbitrary electron density (half of the hydrogen density) to determine the collisional rates. Then, we solve the statistical equilibrium equations to determine hydrogen level populations and obtain new electron densities. The hydrogen densities are adjusted in order to satisfy the pressure equilibrium condition. After a few iterations, we obtain hydrogen and electron densities which are consistent with the intensities.

Then, we compute the optical depths and solve the radiative transfer equations for the continua and the lines which are optically thick. The incident intensities are used as boundary conditions. The Lyman-α and β lines are treated according to standard partial redistribution, while complete redistribution is assumed for other lines. Since the slab is symmetrical, computations are performed on the half-slab only. These computations produce a new set of intensities, which in turn yield new radiative rates, and new populations through the statistical equilibrium equations. In practice, net radiative rates in lines are used to control the convergence, with the help of relaxation parameters. This process is applied 8 times before new hydrogen and electron densities are computed to satisfy pressure and ionization equilibria.

The process stops when some fixed convergence criteria are satisfied both for net radiative rates in lines and radiation temperatures in continua. The maximum number of overall iterations is set to 50, which corresponds to 400 subiterations. In practice, this limit is never reached, the convergence criteria being generally satisfied in less than 150 iterations, except for very thick models.

The model hydrogen atom includes 20 discrete levels plus one continuum, and consequently 190 lines and 20 bound-free transitions. The solution of radiative transfer equations for every permitted transition (line or continuum) needs the specification of the incident intensities in the corresponding frequency range. For the 10 lines formed between the 5 first levels of hydrogen, detailed line profiles are specified in the file 'intinc.dat' (see below). For the other 180 lines and the 20 bound-free transitions, we use mean intensities deduced by interpolation from the table of brightness temperatures of GHV. The solution of the radiative transfer equation is performed when the optical thickness of the slab in the corresponding transition is greater than 0.1. Otherwise, the intensity is assumed to be constant throughout the slab.

Please note that this code is not entirely original. For instance, two functions have been copied directly from the literature: the Voigt function by Humlíček (1982) and the Gaunt factors from Carbon and Gingerich (1969). Many formulae for computing opacities, atomic parameters or redistribution functions are also taken from the literature. The list is too long to be reproduced here, but the references are cited as comment lines in the code.

3. Practical Use of the Code

Two files are necessary to perform the computations: the Fortran 90 code ‘prom4.f’ and the data file for incident intensities ‘intinc.dat’. In the standard version, an additional file ‘model.dat’ is also required to specify the principal parameters of the prominence models.

3.1. Fortran Files

The file ‘prom4.f’ is a Fortran 90 code, which contains all the routines necessary for the computations. Since the main parts of the subroutines were written before the advent of Fortran 90, we kept the standard ‘fixed format’.

This code must be compiled with an option which insures that real numbers are coded in 64 bits. On some computers, like Cray, it is the default option. On many computers, the default option is 32 bits, so that the 64-bit option must be explicitly stated (for instance, on IBM computers of the RS/6000 series, one may use the options ‘-qautodbl=dbl’ or ‘-qrealsize=8’).

There is an alternative file ‘prom4.f.sp’. The only difference is that this code does not read the model parameters from a file "model.dat" but asks the user to enter these data from the keyboard. In this case, a single prominence model is computed at a time.

3.2. Input Files

The file ‘intinc.dat’ is used to define the incident intensities, for the 10 lines formed between level 1 and level 5 of hydrogen. It contains the intensities at the solar disk center, as a function of wavelength, and a set of 6 parameters defining the limb darkening function. We have used the polynomial representation from Pierce and Slaughter (1977) and Pierce, Slaughter and Weinberger (1977):

$$I(\lambda, \mu) = \sum_{i=0}^{5} a_i(\lambda)\mu^i \tag{1}$$

for Balmer and Paschen lines. Br α coefficients have been taken from Allen (1973). When there is no limb darkening (Lyman lines), the coefficients are set to zero.

In the standard file 'intinc.dat', the Lyman lines come from observations by OSO-8 (the same as in GHV). The Balmer lines are taken from the solar atlas of Kitt-Peak 'FTS-Atlas' (Neckel, 1999), neglecting the small lines located in the wings of the hydrogen lines. Since there is no significant difference between computations and available observations in the infrared, we used computed intensities for Paschen and Brackett lines.

There are two alternative files: 'intinc.dat.lines' differs from the preceding one since the small lines (in the wings of Balmer lines) of the FTS-Atlas are included. The profiles are then symmetrized and smoothed. In fact, this does not constitute a definite advantage with respect to the standard file, because some of these small lines are probably of telluric origin.

The third file 'intinc.dat.calc' contains theoretical values computed from the model 'C' of Vernazza, Avrett and Loeser (1981). However, we warn the user that these computed intensities may differ in many respects from observed values.

The other input file ('model.dat') is a very simple file provided by the user which contains, as unformatted data:

– the number of models to be computed

– for each model, a line containing the following 5 parameters: temperature (K), gas pressure (dyn cm^{-2}), thickness (km), microturbulent velocity (km s^{-1}) and altitude (km) above the solar surface.

An example containing 4 models ('model.dat.exam') is given.

3.3. Output Files

There are three output files. The first one, named 'resume.dat' consists of one half-page in ASCII for each model, which recalls the input parameters and gives a summary of the principal results, such as the column mass, the optical depths at the heads of the Lyman and Balmer continua, hydrogen and electron densities and the characteristics of 9 selected lines (the same as in GHV).

The two other output files give the same information, the profiles of the 9 lines and of the Lyman continuum, in two different forms: 'profil.ps' gives this information as PostScript graphics (2 pages per model), while 'profil.dat' gives it as numbers, for personal computer uses. The procedure to read 'profil.dat' is explained in the file 'profil.read'.

For the models specified in 'model.dat.exam' the three corresponding output files are given as: 'resume.dat.exam', 'profil.dat.exam' and 'profil.ps.exam'.

These different files are available on the Web site 'www.medoc-ias.u-psud.fr' under the topics 'MEDOC Science' and 'Radiative Transfer Codes'. The average running times per model have been recorded on 3 different computers. They are indicated in Table I.

TABLE I

Average running times per model (input file: ‘model.dat.exam’).

Computer type	Time (s)
IBM RS/6000 F50	144
IBM RS/6000 SP Nighthawk	45
Hewlett-Packard DCE/9000-780	726

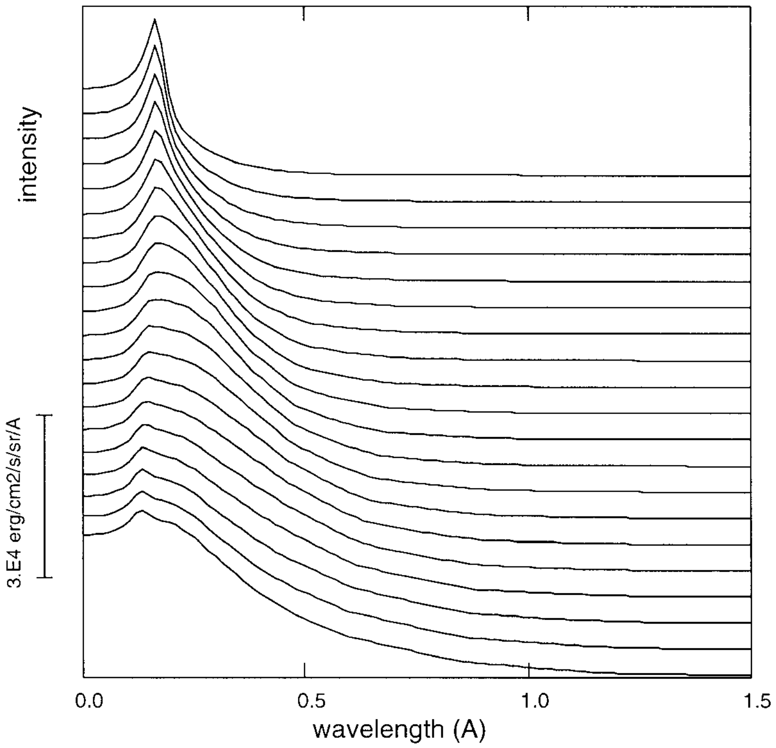

Figure 1. Variations of the Lα profile along a prominence model with variable temperature, pressure and altitude. For clarity, the successive profiles are shifted by a constant quantity (the top curve corresponds to the top of the prominence).

4. Example of Application

A prominence whose physical properties vary with altitude may be simulated by a sequence of individual models. In the present case, we compute successively 20 models to simulate a prominence with a vertical extension of 10^5 km, a temperature increasing from 5000 K at the bottom to 10 000 K at the top, and a pressure decreasing from 0.2 to 0.02 dyn cm^{-2}. The altitude, the logarithm of temperature and the logarithm of pressure vary linearly. Other parameters are constant: the thickness of the prominence is set to 2000 km and the microturbulent velocity to 5 km s^{-1}.

Figure 1 shows the variations of the Lα profile from the bottom to the top of the prominence. Near the bottom, the prominence is very optically thick in Lα (3×10^6) and the emission process is dominated by the scattering of the incident radiation. As the temperature increases and the pressure decreases, the optical thickness decreases (3×10^4 at top). The incident radiation also decreases as the effect of altitude. So, the scattering decreases and the thermal emission of the slab becomes the dominant emission process at the top of the prominence. As a consequence, we obtain a relatively broad and flat profile at the bottom of the prominence, which is similar to the incident profile. As altitude increases, the profile is transformed into a thermal emission profile with sharp peaks and low wings.

5. Conclusion

Some other codes concerning radiative transfer in prominences have been developed at the 'Institut d'Astrophysique Spatiale'. For instance, there is a version of the hydrogen code which allows non-isothermal models and may be used to treat models with a prominence–corona transition region. Another code calculates the emission in Mg II and Ca II lines (Gouttebroze, Vial, and Heinzel, 1997). These codes are presently in a raw form which is not appropriate for public use. They should be released in the near future, after some work is done for refinement.

A code for helium, including incident radiations from the solar corona, has been developed recently (Labrosse and Gouttebroze, 1999; Labrosse, Gouttebroze and Vial 1999). This work is still in progress. Finally, a combined hydrogen–helium NLTE code will replace the present code PROM4, where hydrogen is the only element treated out of LTE.

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References

Allen, C. W.: 1973, *Astrophysical Quantities*, The Athlone Press, University of London.

Auer, L. H. and Mihalas, D.: 1970, *Monthly Notices Royal Astron. Soc.* **149**, 65.

Avrett, E. H. and Loeser, R.: 1987, in W. Kalkofen (ed.), *Numerical Radiative Transfer*, Cambridge University Press, Cambridge, p. 135.

Carbon, D. F. and Gingerich, O.: 1969, in O. Gingerich (ed.), *Theory and Observation of Normal Stellar Atmospheres*, M.I.T. Press, Cambridge, p. 377.

Cuny, Y.: 1967, *Ann. Astrophys.* **30**, 143.

Feautrier, P.: 1964, *C. R. Acad. Sci. Paris* **258**, 3189.

Gouttebroze, P., Heinzel, P., and Vial, J.-C.: 1993, *Astron. Astrophys. Suppl.* **99**, 513 (GHV).

Gouttebroze, P., Vial, J.-C., and Heinzel, P.: 1997, *Solar Phys.* **172**, 125.

Heasley, J. N. and Milkey, R. W.: 1983, *Astrophys. J.* **268**, 398.

Heinzel, P., Gouttebroze, P., and Vial, J.-C.: 1987, *Astron. Astrophys.* **183**, 351.

Humlíček, J.: 1982, *J. Quant. Spectr. Rad. Transfer* **27**, 437.

Labrosse, N. and Gouttebroze, P.: 1999, *Proc. 8th SOHO Workshop, 'Plasma Dynamics and Diagnostics in the Solar Transition Region and Corona'*, ESA SP-446.

Labrosse, N., Gouttebroze, P., and Vial, J.-C.: 1999, *Proc. 9th European Meeting on Solar Physics, 'Magnetic Fields and Solar Processes'*, ESA SP-448.

Neckel, H.: 1999, *Solar Phys.* **184**, 421.

Pierce, A. K. and Slaughter, C. D.: 1977, *Solar Phys.* **51**, 25.

Pierce, A. K., Slaughter, C. D., and Weinberger, D.: 1977, *Solar Phys.* **52**, 179.

Vernazza, J. E., Avrett, E. H., and Loeser, R.: 1981, *Astrophys. J. Suppl. Ser.* **45**, 635.