USER GUIDE

PROM7: Non-LTE radiative transfer in solar prominences and filaments

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Web access:
https://idoc.ias.u-psud.fr/MEDOC/Radiative transfer codes
1 Introduction

The PROM7 code was written in Fortran 77 by P. Gouttebroze ([9], [10], [11], [12]) and describes Non-LTE (NLTE) radiative transfer (1D) in solar prominences and filaments, using partial frequency redistribution for resonance lines of hydrogen and calcium. We solve the equations of radiative transfer, statistical equilibrium of level populations, and ionization equilibrium for hydrogen and calcium atoms using an iterative method.

Prominences and filaments are a same physical phenomenon but viewed from a different perspective. A filament is viewed on the solar disk and a prominence is viewed out of the limb of the disk.

The models of atmosphere considered here are isobaric and isothermal, defined by temperature, $T$, pressure, $P$, microturbulent velocity, $V$, thickness, $e$, altitude, $h$.

For each model of atmosphere ($T, P, V, e, h$ parameters), the formation of hydrogen lines is first considered. Thus, we obtain the electron density and the emergent intensities for hydrogen lines. The electron density is used for the formation of calcium lines. These lines (intensity, profile) are used to diagnose solar prominences and filaments through comparison with observations.

The original version of PROM7, adapted to gfortran compiler, is available from MEDOC website:
https://idoc.ias.u-psud.fr/MEDOC/Radiative transfer codes

In the following sections, we will explain in details PROM7 code (hydrogen + calcium): modeling, implemented equations, algorithm, numerical methods, etc.

2 Description of PROM7 code

Nature of the physical problem: NLTE radiative transfer (1D) in solar prominences and filaments ($HI$ and $CaII$ lines)

Method of solution: Feautrier method with variable Eddington factors

Other relevant information:
- The atmosphere models considered here are isothermal and isobaric defined by $T, P, V, e, h$ (temperature, pression, microturbulent velocity, thickness, altitude)
- Partial frequency redistribution (PRD) is used for resonance lines of hydrogen and calcium, while for the other lines and continua complete frequency redistribution (CRD) is used

Author: P. Gouttebroze

Program available from:
https://idoc.ias.u-psud.fr/MEDOC/Radiative transfer codes

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Computer(s) on which program has been tested: PC with 4 Intel processors (2.67GHz)

Operating System(s) for which version of program has been tested: Linux

Programming language used: Adapted in Fortran 90 for gfortran compiler

Status: stable

Accessibility: open (MEDOC)

No. of code lines in combined program and test deck: \( \sim 8000 \)

Typical running time: \(< 1 \text{ min for 3 atmosphere models (prominence) and } < 13 \text{ mins for 3 atmosphere models (filament)}\)

References:

3 Algorithm

The figure 1 describes the algorithm of PROM7 code.

The algorithm starts with an initialization of physical parameters for hydrogen:

- Statistical equilibrium (see figure 5): \( A_{ji} \) (Einstein \( A \) coefficient), \( B_{ij} \) and \( B_{ji} \) (Einstein \( B \) coefficients), \( C_{ij} \) and \( C_{ji} \) (collisional excitation and deexcitation coefficients)
- Boundary conditions (incident intensities for H lines and continua)
- Radiation temperatures

The first aim of PROM7 code is to calculate the electron density which will be used in the formation of calcium lines. The free electrons are assumed to be obtained by ionization of hydrogen and the other elements (He, metals, etc), represented by the red loop in figure 1. Inside this general loop for hydrogen, the statistical equilibrium is solved by iteration i.e. hydrogen level populations are calculated by taking \( N_e = 1/2 \ N_H \) as a starting value (\( N_e \)
Hydrogen (H I, II):
- Statistical equilibrium: $A_{ji}, B_{ji}, B_{ij}, C_{ij}, C_{ji}$
- Boundary conditions (incident intensities)
  (solar observations) for lines and continua
- Radiation temperatures

For an atmosphere model defined by:
T, P, V, e, h

Calcium (Ca I, II, III):
- Input: $N_e$
- same processing as for $H$
- Output: emerging intensities, $CaII$ line profiles,
  level populations of $Ca$

Figure 1: Algorithm of PROM7 code
and \( N_H \) are electron and hydrogen densities). By iteration, we obtain \( N_e \) and the atmosphere modeling for hydrogen, this one being the most abundant element in prominences or filaments. The hydrogen emergent spectrum is calculated for 3 values of \( \theta \), angle between the light ray and the normal to the solar surface.

After modeling the atmosphere, assuming 90% of hydrogen, we determine the calcium-to-hydrogen line ratios, for which we observe the \( \text{CaII} \) lines. To study a \( \text{CaII} \) line, we need to know all the electronic states of calcium ions. There are only \( \text{CaI} \), \( \text{CaII} \) and \( \text{CaIII} \) ions at the temperature of prominences or filaments, the other being negligible. We can do now radiative transfer in \( \text{CaII} \) lines to obtain \( \text{CaII} \) emergent spectrum for many values of angle \( \theta \) and \( \text{CaI} \), \( \text{CaII} \) and \( \text{CaIII} \) level populations.

4 Prominence modeling

Picture 2 represents an erupting prominence observed by SDO/AIA (2012/08/30) at 304Å and 171Å wavelengths.

In the modeling (see figure 3), a prominence is represented by a symmetric plane-parallel slab (with thickness \( e \)) standing vertically above the solar surface (at altitude \( h \)) and irradiated on both faces by the Sun. It is a 1D representation. Inside the prominence, the initial condition is defined by 3 physical parameters : electronic temperature, \( T \), pressure, \( P \) and microturbulent velocity, \( V \). Due to the symmetry of the problem, calculations can be done in a half slab.

Figure 4 represents the position of a prominence and a filament with respect to the Sun and to the observer. There is a symmetry in the prominence model but not in the filament model.

5 Bound-Free and Bound-Bound transitions

The transitions used in PROM7 code are Bound-Free and Bound-Bound transitions, which are represented in figure 5. Bound-Free transitions are between a bound state \( i \) and a continuum, producing a free electron with energy \( \epsilon \). It starts from excited states limit, i.e. \( \epsilon = 0 \). Bound-Bound transitions are from level \( i \) to level \( j \).
Figure 2: Erupting solar prominence observed by SDO/AIA, at 304Å and 171Å wavelengths, 2012/08/30

\[ h\nu \leq \epsilon \leq h\nu_{\infty} \]

\( A_{ji} \): Einstein A coefficient

i.e. "spontaneous emission probability". \((A_{ij} = 0)\)

\( B_{ij} \): Einstein B coefficient for absorption process

\( B_{ji} \): Einstein B coefficient for induced emission process

\( \epsilon \): energy of the free electron

Figure 5: Transition types used in PROM7
Prominence with thickness $e$

half slab

Symmetric

T, P, V

h

Solar surface

EUV coronal radiation

Boundary conditions (CL)

Incident radiation

EUV coronal radiation

line of sight $Z$

Incident radiation

Figure 3: Prominence model
Position of the prominence with respect to the Sun and to the observer

Position of the filament with respect to the Sun and to the observer

Figure 4: Positions of the prominence (top) and the filament (bottom) with respect to the Sun and to the observer
6 Atomic data

In this section we describe the atomic structure of the following atoms: hydrogen and calcium.

6.1 Hydrogen

The transitions for hydrogen are summarized in Table 1. $NN$ is the number of energy levels, including the threshold level continuum, bound levels limit ($\infty$). $NTT = NN \times (NN - 1)/2$ is the total number of transitions, $NTAC = NN - 1$ is the number of continua (bound-free transitions) and $NTAR = NTT - NTAC$ is the number of lines (bound-bound transitions). In PROM7, $NN = 21$ (20 levels and 1 continuum).

<table>
<thead>
<tr>
<th>Transition</th>
<th>Lower level</th>
<th>Upper level</th>
<th>Transition name</th>
<th>Wavelength $\lambda$(Å)</th>
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</tr>
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</table>

Table 1: Main transitions for hydrogen

6.2 Calcium

For calcium, 7 levels and 7 radiative transitions are considered (see figure 6), corresponding to absorption and emission transitions:
• 1 to 2: ionization from the fundamental state of $CaI$ to the fundamental state of $CaII$
• 2 to 5: $H$ ($\lambda = 3969\text{Å}$)
• 3 to 5: $IR1$ ($\lambda = 8664\text{Å}$)
• 2 to 6: $K$ ($\lambda = 3934\text{Å}$)
• 3 to 6: $IR2$ ($\lambda = 8500\text{Å}$)
• 4 to 6: $IR3$ ($\lambda = 8544\text{Å}$)
• 2 to 7: ionization of $CaII$ (between $CaII$ and $CaIII$ fundamental levels)

![Figure 6: Calcium energy diagram (not to scale) - 7 radiative transitions (red)](image)

7 Population equations and radiative transfer equation

Let's consider level $j$ in figure 5. At equilibrium, the population equations for this level contain all processes of population and depopulation of level $j$ to other levels $i$ which are
balanced:

\[ N_j \sum_{j \neq i}^n P_{ji} = \sum_{j \neq i}^n N_i P_{ij} \]  

(7.1)

For the calcium atom (see figure 6), \( n = 7 \).

The depopulation rate \( P_{ji} \) from level \( j \) is written as:

\[ P_{ji} = A_{ji} + B_{ji} \bar{J}_{ij} + C_{ji} = R_{ji} + C_{ji} \]  

(7.2)

where \( C_{ji} \) is the collisional deexcitation rate, proportional to the electron density. \( R_{ji} \) is the radiative depopulation probability either by absorption and by spontaneous \((A_{ji})\) or by stimulated emission. \( A_{ji} \) and \( B_{ji} \) are corresponding to Einstein coefficients.

The population rate \( P_{ij} \) of level \( j \) can also be written as:

\[ P_{ij} = B_{ij} \bar{J}_{ij} + C_{ij} = R_{ij} + C_{ij} \]

where \( R_{ij} \) and \( C_{ij} \) are similar to \( R_{ji} \) and \( C_{ji} \), except for spontaneous emission \((A_{ij} = 0)\).

The expression of \( \bar{J}_{ij} \) is:

\[ \bar{J}_{ij} = \int_{-\infty}^{+\infty} J_\nu \Phi_\nu \, d\nu \]  

(7.3)

where \( J_\nu \) is the mean intensity integrated over direction \( \mu = \cos \theta \), \( \theta \) being the angle between the light ray and the normal to the solar surface:

\[ J_\nu = \frac{1}{2} \int_{-1}^{1} I_\nu(\mu) \, d\mu \]  

(7.4)

\( \Phi_\nu \) is the normalized profile of the absorption coefficient \((\int \Phi_\nu \, d\nu = 1)\).

The left-hand side term in the population equations (7.1) represents all the processes which depopulate level \( j \) and the right-hand side term corresponds to all the levels which populate the level \( j \). And we use the following closure conservation equation:

\[ \sum_{j=1}^n N_j = N_T \]  

(7.5)

where \( N_T \) is the total population of the atomic element.

These population equations (7.1) which contain the mean intensities via \( \bar{J}_{ij} \) (i.e. integrated over the line profile centered in \( \nu_0 \)) are coupled with the radiative transfer equation (7.6).

The intensity in the radiative transition is obtained by solving the transfer equation:

\[ \mu \frac{dI_\nu}{d\tau_\nu} = I_\nu - S_\nu \]  

(7.6)
\( \tau_\nu \) is the optical depth at frequency \( \nu \), and \( S_\nu \) is the total source function defined by:

\[
S_\nu = \frac{\epsilon_\nu}{\kappa_\nu},
\]

where \( \kappa_\nu \) is the absorption coefficient and \( \epsilon_\nu \) the emission coefficient.

Thus, we obtain a coupled equation system which is solved by numerical methods such as the Feautrier method ([13]). For more details, see the next two sections.

8 Formalism used for radiative transfer

The radiative transfer equations in the lines and continua of hydrogen are solved by a finite-difference method (Feautrier method) with variable Eddington factors. The other equations, namely that of statistical equilibrium of level populations, ionization and pressure equilibria, are solved by iteration. This is basically equivalent to a two-level atom model.

At the beginning, the intensities inside the slab are set by assuming that the medium is optically thin in all transitions (i.e. without radiative transfer). 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.

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-\( \alpha \) and \( \beta \) lines are treated according to standard partial redistribution, while complete redistribution is assumed for other lines. Since the slab is symmetrical, computations are performed in the half-slab only. These computations produce a new set of intensities, which in turn yields new radiative rates, and new populations through the statistical equilibrium equations. In practice, “net radiative rates” (not explained here) in lines are used to control the convergence, with the help of relaxation parameters. This process is applied many 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.

This summary concerns only hydrogen atom. For calcium atom, we solve the radiative transfer equations without computing again the electron density.
9 Subroutine descriptions

The half plane-parallel slab with thickness $1/2 e$ (see figure 3) representing the structure model used in the PROM7 code is divided in $NXMOD = 46$ meshes. For a prominence model ($IVERT = 1$), the total number of meshes is $NZ = NXMOD = 46$ (half slab due to prominence symmetry, see figure 4). For a filament model ($IVERT = 0$), $NZ = 2 \times NXMOD - 1 = 91$ (entire slab).

The PROM7 code starts with the mesh defined above. The main subroutine PROHYD is then called:

- INIMET : calculates metal abundances relative to hydrogen
- Input: isothermal and isobaric atmosphere parameters “model.dat”
- Listing of radiative transitions, lower and upper energy levels
- do imdl = 1, ndml : loop on each model of isobaric and isothermal atmosphere
  I. H modeling
  II. Ca modeling
endo
- output: line profiles given as data (“profil.dat”)
- PSDEB, VISU21P, VISU21L : visualization programs (emergent intensities “profil.ps”).

**Input** files for PROM7:

- intinc.dat : hydrogen incident intensities
- intica.dat : calcium incident intensities
- tembri.dat : other lines of the hydrogen spectrum (Brightness temperatures)
- model.dat : file including the number of models to be computed and for each model, a line containing 5 parameters (temperature ($°$K), pressure (dyn.cm$^{-2}$), thickness (km), microturbulent velocity (km.s$^{-1}$), altitude (km))

**Output** files for PROM7:

- resume.dat : iteration summary
- profil.dat : line profiles given as data
- profil.ps : line profiles as PostScript file
- fort.66 : transition lines

In the next sections, hydrogen and calcium modelings will be explained in details, such as all subroutines called by PROM7 code and a set of variables used in PROHYD subroutine.
9.1 Set of variables used in PROHYD subroutine

- IVER T = 0: filament model (horizontal slab), IVER T = 1: prominence model (vertical slab)
- NMDL: number of atmosphere models to be computed (isothermal and isobaric)
- NXMOD: number of meshes in the half slab
- NZ: total number of meshes
- NFR: number of frequencies in a line
- NMU: number of directions $\mu = \cos \theta$, where $\theta$ is the angle between the light ray and the normal to the solar surface
- NPSOR: number of points for the visualization of line profiles
- NFRC: number of frequencies in a continuum
- NTAB: size of the temperature array $T_{AB}$ (see CAIIP subroutine: for the computation of collision rate coefficients)
- NINF: transition lower level
- NSUP: transition upper level
- ITP: to indicate if the transition is allowed or forbidden
- IOPRN = 1: complete redistribution (CRD), IOPRN = 3: partial redistribution (PRD), IOPRN = 4: PRD with coherent coefficient depending on frequency (particular case for Ly $\alpha$)
- IOPERA = 1: line profiles are printed, IOPERA = 0: line profiles are not printed. IOPERA is linked to DL2 (see below)
- DL1: x-axis (first wavelengths) for line profiles (visualization)
- DL2: y-axis (last wavelengths) for line profiles (visualization)
- IOPMRU = 1: only one redistribution matrix is computed for each transition (the same matrix is used for all meshes), IOPMRU = 0: all the redistribution matrices are computed for each transition (the same matrix is used for all meshes)
- XMOD: array corresponding to the geometry of the half slab
- EPS and BEN: line coupling coefficients
- CSI0 and ETA0: parameters for continua which are equivalent to EPS and EPSxBEN for lines
• GIBAR: mean intensity weighted by absorption profile
• IOPECO: equivalent to IOPERA for continua
• IOPFEV: option for computing variable Eddington factors
• IPROF = 1: optical depths are printed. If not, IPROF = 0
• IOPMIC = 1: microturbulent pressure is taken account. If not, IOPMIC = 0
• NVLI: number of lines to visualize
• IVHYD: visualization option for hydrogen
• INIDLD: option for initializing automatically Doppler widths from temperature of reference TEREF (for graphic representation)
• IOPCAC = 0: without continuum absorption, IOPCAC = 3: continuum absorption is included in computations
• IOPEAC: prints continuum absorption in output file “fort.66”
• IOPATM: prints atmosphere parameters in output file “fort.66”
• IOPTTC: prints continuum transition rates
• PMU: values of $\mu$ (line profiles for $\mu = 1$ are plotted in plain line, for $\mu = 0.6$ in dashed line, and for $\mu = 0.2$ in dotted line)
• IVTR: visualization index for radiative transfer
• ETOT: total energy emitted by prominence or filament in a line
• RDMAT: redistribution matrix
• AJI: Einstein A coefficient i.e. spontaneous emission
• BJI, BIJ: Einstein B coefficients for absorption and induced emission processes
• CIJ, CJI: collisional excitation/deexcitation coefficients
• CAC: continuum absorption coefficient
• TR: radiation temperature for bound-free transition
• FADIR: dilution factor for lines
• FADIC: dilution factor for continua
• CPOL: polynomial coefficients of degree 5 used in the computations of dilution factors (array size : NCMX)

• FEVK and FEVL, FKTC and FLTC: variable Eddington factors (resp. lines and continua)

• HIEMC: intensity emitted in the continuum

• RIK, RKI: radiative transition rates

• FIIR, FISR: lower and upper incident line flux

• FRR: frequency in the line

• Atmosphere parameters (array size NZ) : XM (column-mass), Z (position in the slab), TE (temperature), PG (gas pressure), VT (microturbulent velocity), HNH (hydrogen density: number of atoms per unit volume), HNE (electron density)

• NTR and NTC: discrete and bound-free transition numbers

• ICTR and ICTC: control index for lines and continua

• FRN: level frequency

• XFR and XFRC: division model in frequency for lines and continua

• BRN and BRP: net radiative bracket before and after computations (they are used to control the convergence)

• SR and SC: line and continuum source functions

• STR: total source function (for line and continuum)

• CARR: line absorption coefficient

• COHER: coherent coefficient

• OIS: collisional ionization rate coefficient

• LYL: number of Lyman lines to compute in HYTOCA subroutine

**9.2 Hydrogen modeling (Johnson model, [15])**

Hydrogen modeling is divided into 4 parts:

1. Initialization of atmosphere parameters:
   • Computation of mesh position $Z$
   • INIFEVH: initialization of Eddington factors (lines and continua)
• INIHYV3: initialization of atomic parameters for statistical equilibrium (\(A_{JI}\): Einstein A coefficient, \(B_{IJ}\) and \(B_{JI}\): Einstein B coefficients, \(S_i\) et \(S_e\): ionization and excitation coefficients)

• SOLINH (concerns the isobaric and isothermal atmosphere model): incident intensities (input file “intinc.dat”) and brightness temperatures (input file “tembri.dat”) are read. Line intensities non defined in “intinc.dat” are computed from “tembri.dat”

• INTALT: computation of dilution factors (lines and continua) depending on altitude (\(F_{ADIR}\): dilution factors for lines, \(F_{ADIC}\): dilution factors for continua)

• COLHCF: boundary conditions for hydrogen (intensities)

• Computation of the integral over the line profile \(HJBAR = \int_{-\infty}^{+\infty} J_\nu \Phi_\nu d\nu\)

• INITRI: initialization of radiation temperatures for hydrogen (corresponding to the radiation of a black body) inside the slab from intensities computed before

2. General loop for hydrogen:
   \(do \ ITG = 1, \ ITGMAX:\)

   • HYESV3: computation of hydrogen level populations and electron density

   • \(do \ IT = 1, \ NTAR:\) loop on discrete transitions
     
     RPCDEH: computation of partial and complete redistribution matrices
     
     enddo

   • If \(IOPFEV \geq 3\), Eddington factors for lines and continua are printed via ECRFEV subroutine

   • Parameters storage for lines (\(HJBAR\) and \(BRN\) (net radiative bracket)) and continua (radiative excitation/ionization probabilities \(RIK\) and \(RKI\)) and for hydrogen level populations \(HN\)

   • \(do \ icr = 1, \ ICRMAX:\) loop on pressure equilibrium

   Ionization of hydrogen determines free electron density.

   – EQSTHV3: Solution of statistical equilibrium equations for hydrogen excited level populations (\(HN\)). More precisely, statistical equilibrium is computed again because some transition coefficients \(P_{ji}\) defined by (7.2) changed (for lines and continua)

   – Bound-Free transitions:

     * \(do \ itac = 1, \ NTAC:\) loop on continua

       • HCONTI: NLTE radiative transfer for continua. Intensities and transition probabilities \(P_{ji}\) defined by (7.2) are computed

     * enddo (for itac)

     * COMPACH: comparison for convergence
Bound-Bound transitions:

* do itar = 1, NTAR: loop on lines
  - RPRHCF: NLTE radiative transfer for lines
* enddo (for itar)
* COMPARCH: comparison for convergence
* Preparation of the next iteration: radiative transition coefficients $RIK$
  are computed from radiation temperature $TR$ calculated before,
  NOVRIK: for continua
  NOVBRV3: for lines.

* enddo (for icr)
* NOVTR2: computation of new radiation temperature for bound-free transitions
* Convergence and parameters storage for $HJBAR$, $HN$, $BRN$, $RIK$, $RK$I

enddo (for ITG)

3. Prints Eddington factors $FEVK$ (lines) and $FKTC$ (continua)

4. Output results: quantities are computed once again in order to obtain convergence
   results at the last iteration. Line profiles from results obtained at the last iteration are
   computed.

  - EXOATM: prints atmosphere parameters (pressure, altitude, electron temperature, hydrogen density, etc)
  - ABSCON: continuum absorption due to different elements is computed (defined in INIMET subroutine)
  - EQSTHV3
  - For lines
    - RPCDEH
    - RPRHCF
    - SUMRA: prints wavelengths $AMBDA$, etc
    - PROFIL: line profiles (prominences)
    - PROEM2: line profiles (filaments)
  - For continua
    - HCONTI
  - COMPARH
  - COMPACH
  - SFTEST

Subroutines called above are explained in the next paragraph.
INIMET

INIMET computes total weight $C_1$ of elements and total abundance $C_2$ with respect to hydrogen of the $NEL = 20$ following elements: He, C, N, O, Ne, Na, Mg, Al, Si, P, S, Ar, K, Ca, Cr, Mn, Fe, CO, Ni, H.

Outputs : $C_1$ and $C_2$

INIFEVH

Initialization of line ($FEVK$ and $FEVL$) and continua ($FKTC$ et $FLTC$) Eddington factors at each frequency and for each mesh.

Inputs : $NZ$ (number of meshes), $NTAR$ (number of lines), $NTAC$ (number of continua), $NFRC$ (number of frequencies in a line), $NFRC$ (number of frequencies in a continuum)

Outputs : $FEVK$, $FEVL$, $FKTC$ and $FLTC$

INIHVV3

Computation of hydrogen atomic parameters for statistical equilibrium: Einstein $A$ and $B$ coefficients for photons ($AJI$, $BIJ$, $BJI$: independent of electron temperature), collisional excitation and ionization rate coefficients ($OIS$ in PROM7 code) for electrons, called $S_e$ and $S_i$ in the formulas below. These coefficients are independent of electron temperature.

The model used for hydrogen is L.C. Johnson model ([15]).

$AJI$ is obtained by AEMS function (in PROM7 code) which is calculated from “Gaunt factors” (Table 1 in [15]).

$BJI$ is obtained from $AJI$, $BIJ$ is such that $\omega_iB_{ij} = \omega_jB_{ji}$, where $\omega_i$ is the statistical weight associated to level $i$.

Computation of collisional excitation rate coefficients (CECH function in PROM7 code):

Let $n$ and $n'$ be two levels ($n < n'$). The excitation rate coefficient is given by the following formula (Johnson, [15]), implemented in PROM7 code:

$$S_e(n, n') = (8kT/\pi m)^{1/2} \frac{2n^2}{x} \pi a_0^2 y^2 \left( A_{nn'} \left[ \left( \frac{1}{y} + \frac{1}{2} \right) E_1(y) - \left( \frac{1}{z} + \frac{1}{2} \right) E_1(z) \right] \right)$$

$$+ (8kT/\pi m)^{1/2} \frac{2n^2}{x} \pi a_0^2 y^2 \left( B_{nn'} - A_{nn'} \ln \frac{2n^2}{x} \left[ \frac{1}{y} E_2(y) - \frac{1}{z} E_2(z) \right] \right)$$

$$E_i(z) = \int_1^\infty e^{-zt} t^{-i} dt$$ is called Exponential integral of order $i$ ($i = 0, 1, 2, ...$).

$m$ denotes the electron mass and $a_0 = 0.5292 \times 10^{-8} \text{ cm}$ the Bohr radius.
Here and below, $E_n$ denotes level energy of $n$ for hydrogen. We obtain:

\[
\begin{align*}
y &= (E_n' - E_n)/kT, \\
z &= r_{nn'} + y, \\
x &= 1 - (n/n')^2, \\
B_{nn'} &= \frac{4n^4}{n'^3} x^{-2} (1 + \frac{4}{3} x^{-1} + b_n x^{-2}), \\
b_n &= n^{-1}(4 - 18.63n^{-1} + 36.24n^{-2} - 28.09n^{-3}), \quad n \geq 2, \\
A_{nn'} &= 2n^2 x^{-1} f_{nn'}, \\
f_{nn'} &= \frac{32}{3\sqrt{3}} \frac{n}{\pi n^3} x^{-3} g(n, x), \\
g(n, x) &= g_0(n) + g_1(n) x^{-1} + g_2(n) x^{-2}, \\
r_{nn'} &= r_n x, \\
r_n &= 1.94n^{-1.57}
\end{align*}
\]

where $g_0$, $g_1$, $g_2$: Gaunt factors for pour Bound-Free transitions. They are given in Table 2 (Table 1 in [15]) :

<table>
<thead>
<tr>
<th>$n$</th>
<th>$g_0(n)$</th>
<th>$g_1(n)$</th>
<th>$g_2(n)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.11330</td>
<td>-0.4059</td>
<td>0.07014</td>
</tr>
<tr>
<td>2</td>
<td>1.0785</td>
<td>-0.2319</td>
<td>0.02947</td>
</tr>
<tr>
<td>$n \geq 3$</td>
<td>0.9935 + 0.2328n$^{-1} - 0.1296n^{-2}$</td>
<td>$-n^{-1}(0.6282 - 0.5598n^{-1} + 0.5299n^{-2})$</td>
<td>$n^{-2}(0.3887 - 1.181n^{-1} + 1.470n^{-2})$</td>
</tr>
</tbody>
</table>

Table 2: Gaunt factors

**Computation of collisional ionization rate coefficients (CICH function in PROM7 code):**

Let us consider here level $n$. Ionization rate coefficient is given by the following formula (Johnson, [15]) implemented in PROM7 code:

\[
S_i(n) = (8kT/\pi m)^{1/2} 2n^2 \pi a_0^2 g_n^2 A_n \left[ \frac{1}{y_n} E_1(y_n) - \frac{1}{z_n} E_1(z_n) \right] + (8kT/\pi m)^{1/2} 2n^2 \pi a_0^2 g_n^2 (B_n - A_n \ln 2n^2) [\zeta(y_n) - \zeta(z_n)],
\]

where $m$ is the electron mass and

\[
\begin{align*}
y_n &= I_n/kT, \\
z_n &= r_n + I_n/kT, \\
\zeta(t) &= E_0(t) - 2E_1(t) + E_2(t)
\end{align*}
\]
\[ I_n \] is ionization energy of level \( n \) for hydrogen.

**Inputs:** \( NZ, NN, NTT, NTAR, NTAC, NFRC, NTAB, INIDLD, ICTR, VTUR, TSLAB, NTR, NTC, TAB, IVISU \)

**Outputs:** \( AJI, BIJ, BJI, OIS, DLDREF \) in frequency and \( DNDREF \) in wavelength (Doppler width for Bound-Free transitions). Initialization of \( BRP, BRN, FPES, CAC, SC, DCAC \)

**SOLINH**

Definition of incident intensities for hydrogen lines in order to provide boundary conditions for the solution of radiative transfer equations.

The input file “intinc.dat” contains incident intensities for \( NLI = 17 \) hydrogen lines. The input file “tembri.dat”, which is a table of brightness temperatures, is used to compute intensities \( FINT \) for the other hydrogen lines which are not in “intinc.dat”.

**Inputs:** \( NN, NTT, NTAR, NFIMX, NCMX, NINF, NSUP, NFR, NTR, ICTR, NFINT \)

**Outputs:** \( FINT, CPOL, FRFI \)

**INTALT**

Computation of dilution factors taking into account the limb darkening and prominence altitude. There is no obvious limb darkening for Lyman lines.

**Inputs:** \( ALTI, NTAR, NTAC, NCMX, CPOL \)

**Outputs:** \( FADIR \) (for lines) and \( FADIC \) (for continua).

**COLHCF**

Boundary conditions (hydrogen) for Bound-Free (continua) and Bound-Bound (lines) transitions.

For lines: lower boundary condition \( FIIR \) is null for prominence models and equal to \( 2 \) \( FADIR \times FLJ \) for filament models. \( FLJ \) is the solar flux (intensity) and \( FADIR \) is the dilution factor (see **INTALT** subroutine). Upper boundary condition \( FISR \) is equal to \( FADIR \times FLJ \) for prominence models and null for filament models. Moreover, natural broadening is computed (associated to level lifetime) for permitted lines by adding the \( AJI \) concerned (inverse of level lifetime). This broadening enables the computation of the profile \( \Phi_\nu \). Profile line is renormalized (intensity): \( GIOM = \int J_\nu \phi_\nu \, d\nu \).
For continua: lower boundary condition $F_{IIC}$ is null for prominence models and is equal to $2B_\nu \times F_{ADIC}$ for filament models. $F_{ADIC}$ is the dilution factor dilution (see INTALT subroutine) and $B_\nu$ is the Planck function. Upper boundary condition $F_{ISC}$ is equal to $B_\nu \times F_{ADIC}$ for prominence models and null for filament models.

Inputs: $IVERT$, $NZ$, $NN$, $NTT$, $NTRD$, $NTRC$, $NFR$, $NFRC$, $NF1MX$, $ITRD$, $ICTR$, $NINF$, $NSUP$, $FRN$, $DNDREF$, $XFR$

Output: $GIOM$

**INITR1**

Initialization of radiation temperature ($TR$) corresponding to photoionization rates in hydrogen Bound-Free transitions, from incident radiation temperature and dilution factor $F_{ADIC}$. We assume at the beginning that the medium is optically thin in all transitions. The photoionization cross-section $SEP$ for hydrogen is obtained from Gaunt factors ([8]). Radiation temperature changes during the iterative process.

Inputs: $NZ$, $NN$, $NTT$, $NTAC$, $NFRC$, $NTC$, $NINF$, $FRN$, $XFRC$, $FADIC$, $RIK$, $TE$

Output: $TR$

**HYESV3**

Solution of statistical equilibrium and ionization for given temperatures and pressures: hydrogen level populations and electron density are computed. For filament models, a term due to microturbulence is included in pressure calculation. The 4 following subroutines are called in HYESV3:

- **TXCOLL**: collisional transition probabilities ($CIJ$ et $CJI$) are computed by using electron density.
- **INIRIKH**: photoionization probabilities $RIK$ (photoionization) and $RKI$ (radiative recombination) are computed. Electron density is used for recombination but not for photoionization.
- **EQSTHV3**: solution of statistical equations for hydrogen level populations by iteration. We obtain a linear system to solve. Output: $HN$ for each level and mesh.
- **SAHARA**: computation of electron density $HNE$ and density of the other elements $HNION$. Saha law at LTE gives the ionization degree of each ion. We use here $HNH$ (and not $HN$).

Inputs for HYESV3: $NZ$, $NN$, $NTT$, $NTAR$, $NTAC$, $NFRC$, $C1$, $C2$, $ITP$, $NINF$, $NSUP$, $NTC$, $FRN$, $POM$, $XFRC$, $Z$, $XM$, $TE$, $VT$, $HNH$, $HNE$, $HN$, $NTAB$, $TAB$
Outputs for HYESV3: $CIJ, CJI, RIK, RKI, HNE, HNION$

**ABSCON**

ABSCON is called when $IOPCAC = 3$ (radiative transfer doesn’t take into account this effect). ABSCON computes continuum absorption in the neighbourhood of lines under consideration and uses PROFSC subroutine.

**PROFSC** : computes additional optical depth $TAUC$ (due to continuum absorption process), continuous source functions $FSC$, coherent scattering ratios $CSCAT$ for a given frequency $FREQ$, and continuous absorption coefficient $CABCO$.

To compute $CABCO$, we need continuum absorption (LTE) by hydrogen negative ions, aluminium, hydrogen (photoionization cross-section $SEPION$ is computed from Gaunt factors ([8])), carbon, magnesium, silicium and iron.

Inputs: $IVISU, NZ, NN, NTT, NTRD, NNHYD, TE, Z, HNH, HNE, XNHYD, ITRD, NINF, NSUP, FRN, SC, DCAC, CAC$

Outputs for ABSCON: $TAUC, FSC, CSCAT, CABCO$

**RPCDEH** (for resonance lines)

Hydrogen partial redistribution. Broadening constants for lines (natural and collisional) are computed.

RPCDEH uses the following subroutines:

**ELCOH1** : computation of collisional broadening $DFRCO$ for hydrogen lines

**COHEVA** : computation of coherent coefficient for different frequencies of $Ly\alpha$ line (H)

**MARALA** : computation of the redistribution matrix for $Ly\alpha$ line

**MAREDI** : computation of the redistribution matrix for the other lines (case of a resonance line with a frequency-independent coherence coefficient)

Inputs for RPCDEH: $IRS, IOPMRU, NZ, NN, NTT, NTRD, NFR, IVISU, IOP, ITRD, NINF, NSUP, FRN, AE, TE, VT, HNE, HN, DND, AM, COHE, FR, PHIX$

Outputs for RPCDEH: $RDMA T$ (redistribution matrix)

**ECRFEV**

Prints variable Eddington factors $FEVK$

**HCONTI**

Solution of NLTE radiative transfert equations for hydrogen Bound-Free transitions in order to compute intensities and transition probabilities ($P_{ji}$ is proportional to intensities and is
used for statistical equilibrium).

HCONTI uses the following subroutines:

**CSIETA**: computation of $CSI_0$ and $ETA_0$ which are for continua, the equivalents of $\epsilon$ and $\epsilon \times B$ for lines (coupling coefficients)

**PROFSC**: see ABSCON subroutine

**TFCFEV**: solution of radiative transfer equations for continua, with external absorption sources (outputs: intensity $GI$ inside the slab and mean intensity $GIBAR$) and source functions $S$. We use Feautrier method and variable Eddington factors

**NOVFEV**: computes new Eddington factors (outputs: $FEVK$ et $FEVL$) from source functions ([3]). This subroutine concerns only discrete and Bound-Free transitions

**TFCOM**: is equivalent to TFCFEV subroutine in the case where the medium is optically thin (outputs: $GI$, $GIBAR$ and $S$)

**TRALA**: computes emergent intensity $HIEMC$ (integral of the source function) by using transition probabilities

Inputs for HCONTI: $IT$, $IVER$, $NZ$, $NN$, $NTT$, $NTAR$, $NTAC$, $NFRC$, $NMU$, $NMUV$, $IOPECO$, $IOPFEV$, $ITP$, $NTC$, $NINF$, $FRN$, $FRC$, $POM$, $TE$, $HNH$, $HNE$, $Z$

Outputs for HCONTI: $HIEMC$ (emergent intensity) and $RIKP$ (transition probabilities for continua)

**COMPACH**

Comparison for convergence: $RIK$ (hydrogen radiative transition parameter at previous iteration) is compared with $RIKP$ (parameter at final iteration)

**RPRHCF**

Radiative transfer is computed for hydrogen lines.

RPRHCF uses the following subroutines:

**EPSBHV3 (preparation for radiative transfer)**: computation of coupling coefficients $BEN$ for a hydrogen two-level atom model (output: $BEN$). $BEN$ is used to transform intensity into source function which is useful to calculate emergent intensity.

**TFRFEV**: solution of NLTE radiative transfer equations for lines using Feautrier method (finite-difference method) and variable Eddington factors. The intensities inside meshes and source functions are computed (outputs: main intensity $GIBAR$ and intensity inside the slab $GI$. We deduce source function $SR$ in the line and the total source fonction $STR$)

**NOVFEV**: computes the new Eddington factors $FEVK$ and $FEVL$ (see HCONTI subroutine)

Inputs for RPRHCF: $IRS$, $NZ$, $NN$, $NTT$, $NTRD$, $NTRC$, $NFR$, $NMU$, $IVER$, $Z$, $TE$, $NTR$, $NINF$, $NSUP$, $AJI$, $BIJ$, $BJI$, $HJBAR$
Outputs for RPRHCF: BEN (coupling coefficient for lines), SR and STR (source functions), GI and GIBAR (intensity inside the slab and mean intensity), BRN1 (Net Radiative Bracket)

COMPARH
Comparison for convergence: BRN (at previous iteration) is compared with BRP (at final iteration). BRN is linked to statistical equilibrium and is calculated as a function of intensities.

NOVRIK
Computation of radiative transition coefficients for continua.
Input: NZ, NTAC, ICTC, RXIK, RIKP
Output: RIK

NOVBRV3
Computation of radiative transition coefficients for lines.
Inputs: NZ, NTRD, ICTR, RXRO
Output: BRN0

NOVTR2
Update of radiation temperature (TR) for hydrogen Bound-Free transitions.
Inputs: ITG, IVTR, RXTR, NZ, NN, NTT, NTAC, NFRC, ICTC, NTC, NINF, FRN, XFRC, RIKP, TE
Output: TR

PROFLI
Computation of emergent line profiles for different values of $\mu = \cos \theta$ in filament case.
Inputs: IRS, NZ, NN, NTT, NTRD, NFR, NMUV, NPSOR, ITRD, NINF, NSUP, FRN, DL1, DL2, PMU, FR, STR, DND, AM, CAR, CAC, TO, NFINT, FRFI, FINT, TOTO, ETOT, FWHM
Outputs: \(XX\) (wavelength range), \(YY\) (emergent intensity)

**PROEM2**

Computation of emergent line profiles for different values of \(\mu = \cos \theta\) in prominence case.

Inputs: \(IRS, NZ, NN, NTT, NTRD, NFR, NMUV, NPSOR, ITRD, NINF, NSUP, FRN, DL1, DL2, PMU, FR, STR, DND, AM, CAR, CAC, TO, IVERT, NFINT, FRFI, FINT\)

Outputs: \(XX\) (wavelength range), \(YY\) (emergent intensity)

**SFTEST**

Prints source functions \(SPOPS\) at the surface of prominence/filament (computed from \(HN\)) and at the center of the slab \(SRADS\) (calculated from intensities \(GI\) inside the slab).

### 9.3 Calcium modeling

The calcium modeling is divided into 4 parts:

- **HYTOCA**: subroutine which performs the transition from H to Ca. Calcium data are prepared: mean intensity is calculated with respect to wavelength, absorption and emission coefficients linked to continua and to pure diffusion are also computed. Solar spectrum is calculated again (intensity, H line profile, ...)

- **POP31**: prints mesh positions \(Z\), H level populations \((HN)\), electron density \((HNE)\), hydrogen total density \((HNH)\)

- **RESUMH**: prints atmosphere parameters \((TSLAB, PSLAB, E PST, VTUR, HKM)\), column-mass, optical thickness for Lyman and Balmer continua, hydrogen and electron densities at the surface of the slab, hydrogen and electron densities in the middle of the slab. Computation of mean electron density \(HNEM\) and emission mesure \(EMEU\)

- **CAIIP**: calcium modeling. The electron density is not calculated any more. We apply the same processing as for hydrogen, i.e.: emergent intensities for Ca II lines are computed, we do radiative transfer for Ca II lines. Moreover, calcium level populations are computed.

Subroutines called before are explained in next paragraph.

**HYTOCA**

Transition from H to Ca. Absorption and emission coefficients linked to continua and to pure diffusion are computed. HYTOCA uses the following subroutines:
PROFSC: see ABSCON subroutine

SERLYM2: computation of absorption (CAB) and emission (CEM) coefficients due to Lyman lines at frequency \( FREQ \). We add the different components (for Lyman lines). Populations \( HN \) are not used.

FONSOC4: computation of internal mean intensity \( GINU = J_\nu = \frac{1}{4\pi} \int I_\nu \, d\omega \) (\( \omega \) is the solid angle) from source function \( SF \), incident intensities (\( HIINF, HISUP \)) and optical depth \( TAUC \) via SF2JNU subroutine

Inputs for HYTOCA: \( LYL, IVERT, NZ, NN, NTAR, NFR, HKM, TE, Z, HNH, HNE, HN, FRN, FRR, DNDR, AMR, SR, CARR, NNHYD, NLAMX, NLA, XNHYD, XLA, GINU \)

Outputs for HYTOCA: \( CABF \) et \( CEBF \) (absorption and emission coefficients for continua), \( CADP \) (coefficients for pure diffusion)

CAIIP

Processing for Ca II lines. CAIIP uses the following subroutines:

INIMET: see hydrogen modeling.

Here are some definitions of variables used in CAIIP subroutine:

- \( ABOND \): abundance of Ca relative to H
- \( INF \): array which contains 1 (if it is a fundamental level) and 0 (if it is an intermediary level)
- \( POM \): weights of each calcium level
- \( FRN \): frequency of levels
- \( ITC \): transition number for which collision rate coefficients are computed
- \( TAB \): array of size \( NTAB \) containing electron temperatures which are used as reference temperatures to array \( OIS \)
- \( OIS \): collisional ionization rate coefficients for each transition and temperature \( TAB \)
- \( OREF \): wavelength array (Å) for each continuum transition
- \( ALP \): photoionization cross-section for continuum

SOLICA: reads input file “intica.dat” (incident intensities corresponding to wavelengths for Ca II)

INIFEV: see hydrogen modeling

INITES: classification of calcium transitions. \( NN = 7 \) levels and \( NTT = 21 \) transitions are considered. Among the permitted transitions, 5 lines and 2 continua are treated.

Total
density of calcium ($HNT$) and continuum absorption are computed (see hydrogen modeling, more precisely ABSCON subroutine). Outputs: $BRN2$, $BRN1$, $HN$, $DNDREF$, $DLDREF$, $CAC$.

**EXOATM:** see hydrogen modeling

**INIRIK2:** computation of radiative transition probabilities for calcium continua from $GINU$ obtained by HYTOCA subroutine. Outputs: $RIK$, $RKI$

**TXCOLL:** see hydrogen modeling

**ECRITAUS:** prints collisional transition rates ($CIJ$, $CJI$), net radiative brackets ($BRN1$, $BRN2$) for Ca II lines

**COLIMI:** boundary conditions (calcium) for Bound-Bound transitions. Lower boundary condition $FIINF$ is null in prominence case and is equal to $2\, FADI \times FLJ$ in filament case. $FADIC$ is the dilution factor and $FLJ$ the solar flux (intensity). Upper boundary condition $FISUP$ is null in prominence case and is equal to $FADI \times FLJ$ in filament case. There is no radiative transfer for calcium continua.

**RPCDEF:** equivalent to RPCDEH subroutine for hydrogen. RPCDEF computes redistribution matrix and uses $ELCO$ (computation of collisional broadening for Ca II lines) and $MAREDI$ (see hydrogen modeling) subroutines

**EQSTGV3:** equivalent to EQSTHYV3 subroutine for hydrogen

**RPRGCF:** equivalent to RPRHCF subroutine for hydrogen

**COMPAR:** comparison for convergence. $BRN1$ is compared to $BRN2$

**NOVBRN:** computation of $BRN1$

The end of CAIIP subroutine is the same as hydrogen, i.e. we compute once again quantities in order to obtain convergence results at last iteration and line profiles (hydrogen and calcium). More precisely, for Ca II lines, the following subroutines seeing before are used: RPRGCF, ECRFEV, SUMRA, PROFLI, PROEM2, POP31, SFTEST.

## 10 Results for hydrogen and calcium lines in prominences

We consider the following isobaric and isothermal atmosphere defined by:

$$T = 10000^\circ K, \ V = 5 \ \text{km.s}^{-1}, \ h = 10000 \ \text{km}, \ e = 200 \ \text{km}, \ P = 0.5 \ \text{dyn.cm}^{-2}$$

In section 10.1 and 10.2, the half-profiles for hydrogen and calcium lines obtained by PROM7 code are given for the atmosphere model described above.

The half-profiles are given for 3 values of $\mu = \cos \theta$.

The half-profile for $\mu = 1$ is plotted by a plain line. The half-profile for $\mu = 0.6$ is plotted by a dashed line and the half-profile for $\mu = 0.2$ by dotted line.

The following figures for hydrogen and calcium lines are stored in the folder **results** when you download the package source file PROM7_PRD.tgz from MEDOC website.

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10.1 Hydrogen

Figure 7: Half-profile of $L\alpha$ line at 1215Å

Figure 8: Half-profile of $L\beta$ line at 1025Å
Figure 9: Half-profile of $H\alpha$ line at 6564Å

Figure 10: Half-profile of $L\gamma$ line at 972Å
Figure 11: Half-profile of $H\beta$ line at 4862Å

Figure 12: Half-profile of $Pa - \alpha$ line at 18756Å
Figure 13: Half-profile of $H\gamma$ line at 4341Å

Figure 14: Half-profile of $Pa - \beta$ line at 12821Å
Figure 15: Half-profile of $H\delta$ line at 4102Å

Figure 16: Half-profile of $H\epsilon$ line at 3971Å
10.2 Calcium

The half-profile are given for 3 values of \( \mu = \cos \theta \).
The half-profile for \( \mu = 1 \) is plotted by a plain line. The half-profile for \( \mu = 0.6 \) is plotted by a dashed line and the half-profile for \( \mu = 0.2 \) by dotted line.

Figure 17: Continuum spectrum at 911Å. Note the change of intensity unit

Figure 18: Half-profile of \( H \) line at 3969Å for \( CaII \)
Figure 19: Half-profile of $IR_1$ line at 8664 Å for CaII

Figure 20: Half-profile of $K$ line at 3934 Å for CaII
Figure 21: Half-profile of IR2 line at 8500 Å for CaII

Figure 22: Half-profile of IR3 line at 8544 Å for CaII
11 Running PROM7

- Download the package source file PROM7_PRD.tgz from MEDOC website: https://idoc.ias.u-psud.fr/MEDOC/Radiative transfer codes
- gfortran compiler is required.
- Unpack the package by typing the following linux command:
  `tar -xvzf PROM7_PRD.tgz`
- Go to folder PROM7_PRD:
  `cd PROM7_PRD`
- The folder contains the following files: intica.dat, intinc.dat, model.dat, tembri.dat, makefile, pr7prd.f90
- The file to modify is “model.dat” : the first parameter corresponds to the option for prominence (= 1) or filament (= 0) and the second parameter represents the number of models to be computed. These models defined below are defined by temperature, pressure, structure thickness, microturbulent velocity and altitude
- Run the code by typing:
  `make
  ./pr7prd`
- The output files are: resume.dat, profil.dat, profil.ps, fort.66 (transitions list)
- The folder results contains the output files corresponding to a test case to be able to check if your results are good.

12 CPU time

For 3 atmosphere models:

- \( T = 6000^\circ K, \ V = 5 \ km.s^{-1}, \ h = 10000 \ km, \ e = 200 \ km, \ P = 0.01 \ dyn.cm^{-2} \)
- \( T = 8000^\circ K, \ V = 5 \ km.s^{-1}, \ h = 10000 \ km, \ e = 200 \ km, \ P = 0.1 \ dyn.cm^{-2} \)
- \( T = 10000^\circ K, \ V = 5 \ km.s^{-1}, \ h = 10000 \ km, \ e = 200 \ km, \ P = 0.5 \ dyn.cm^{-2} \)

On a PC with 4 Intel processors (2.67 GHz):
• CPU time for the 3 prominence models defined above: 53.662 s < 1 min

• CPU time for the 3 filament models defined above: 781.313 s ~ 13 mins, because in filament case, calculations are made in the entire slab and not in the half slab as for prominence case.

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28th September 2015
M. C-Y
References


