USER GUIDE

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

Martine Chane-Yook

martine.chane-yook@ias.u-psud.fr

Reviewed by:

Jean-Claude Vial
Pierre Gouttebroze
Jacques Dubau

Web access:

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

Contents

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, pression, P, microturbulent velocity, V, thickness, e, altitude, h.

For each model of atmosphere (T, P, V, e, and 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

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: ~ 8000

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

References:

- P. Gouttebroze, P. Heinzel and J.-C. Vial, "The hydrogen spectrum of model prominences", A&A Sppl. Ser., 99, 513-543, 1993
- P. Gouttebroze and P. Heinzel, "Calcium to hydrogen line ratios in solar prominences", A&A, 385, 273-280, 2002

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

General loop
for hydrogen

Loop on statistical
equilibrium(ionization included)
- computation of H level
populations

Radiative
transfer:
H continua

Radiative
transfer:
H lines

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

Output:
- N_e (electron density)
- Level populations of H

H emergent intensities
and line profiles
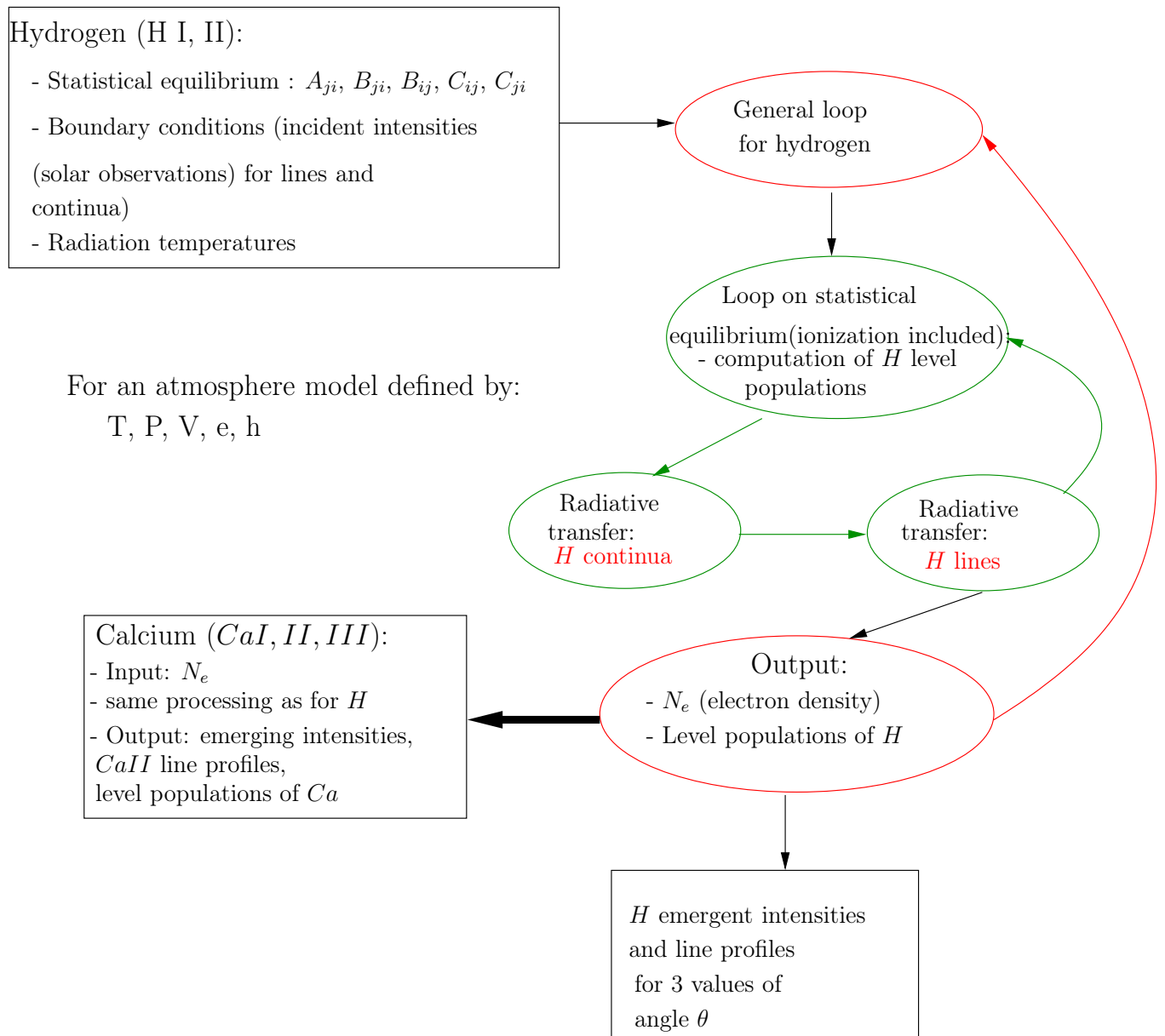for 3 values of
angle θ

Figure 1: Algorithm of PROM7 code

4

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 abondant element in prominences or filaments. The hydrogen emergent spectrum is calculated for 3 values of θ, 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 $CaII$ lines. To study a $CaII$ line, we need to know all the electronic states of calcium ions. There are only CaI, $CaII$ and $CaIII$ ions at the temperature of prominences or filaments, the other being negligeable. We can do now radiative transfer in $CaII$ lines to obtain $CaII$ emergent spectrum for many values of angle θ and CaI, $CaII$ and $CaIII$ 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, pression, 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 ϵ. It starts from excited states limit, i.e. $\epsilon = 0$. Bound-Bound transitions are from level i to level j.
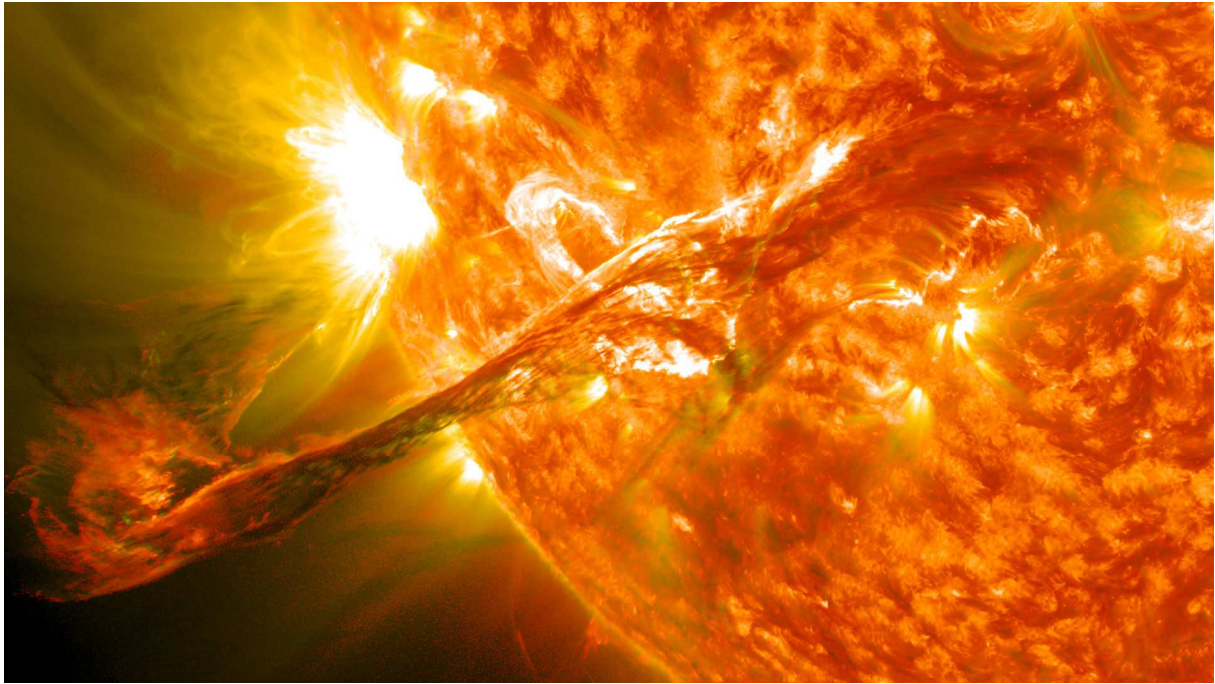
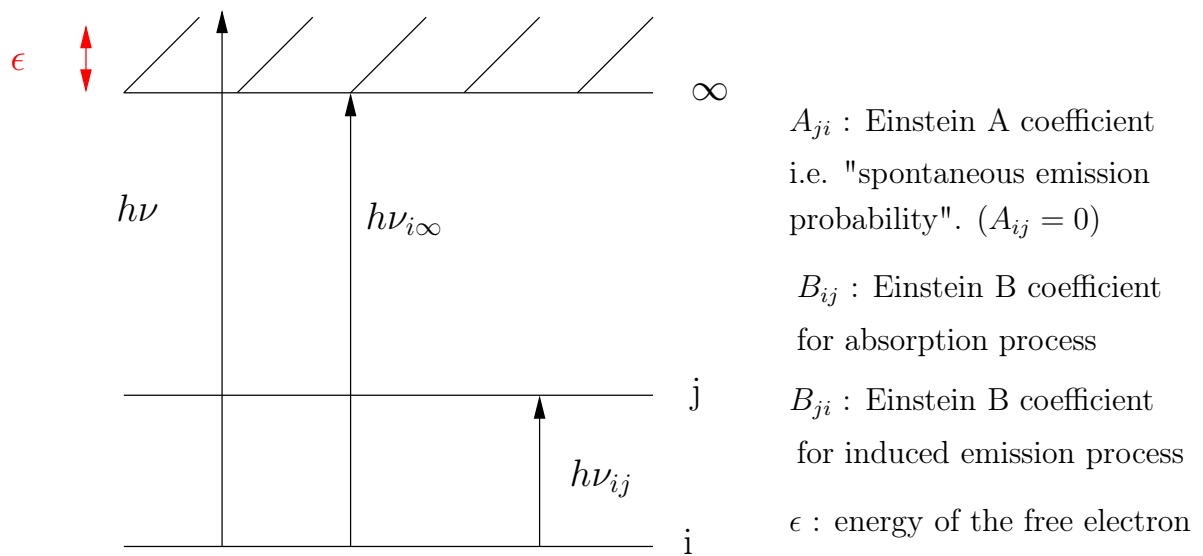Figure 2: Erupting solar prominence observed by SDO/AIA, at 304Å and 171Å wavelengths, 2012/08/30

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

ϵ : energy of the free electron

Figure 5: Transition types used in PROM7

Prominence with thickness e

half slab

EUV coronal radiation

EUV coronal radiation

Symmetric

T, P, V

Boundary conditions (CL)

line of sight Z

Incident radiation

Incident radiation

h

Solar surface

Figure 3: Prominence model

EUV coronal radiation

Observer

Line of sight

Incident radiation

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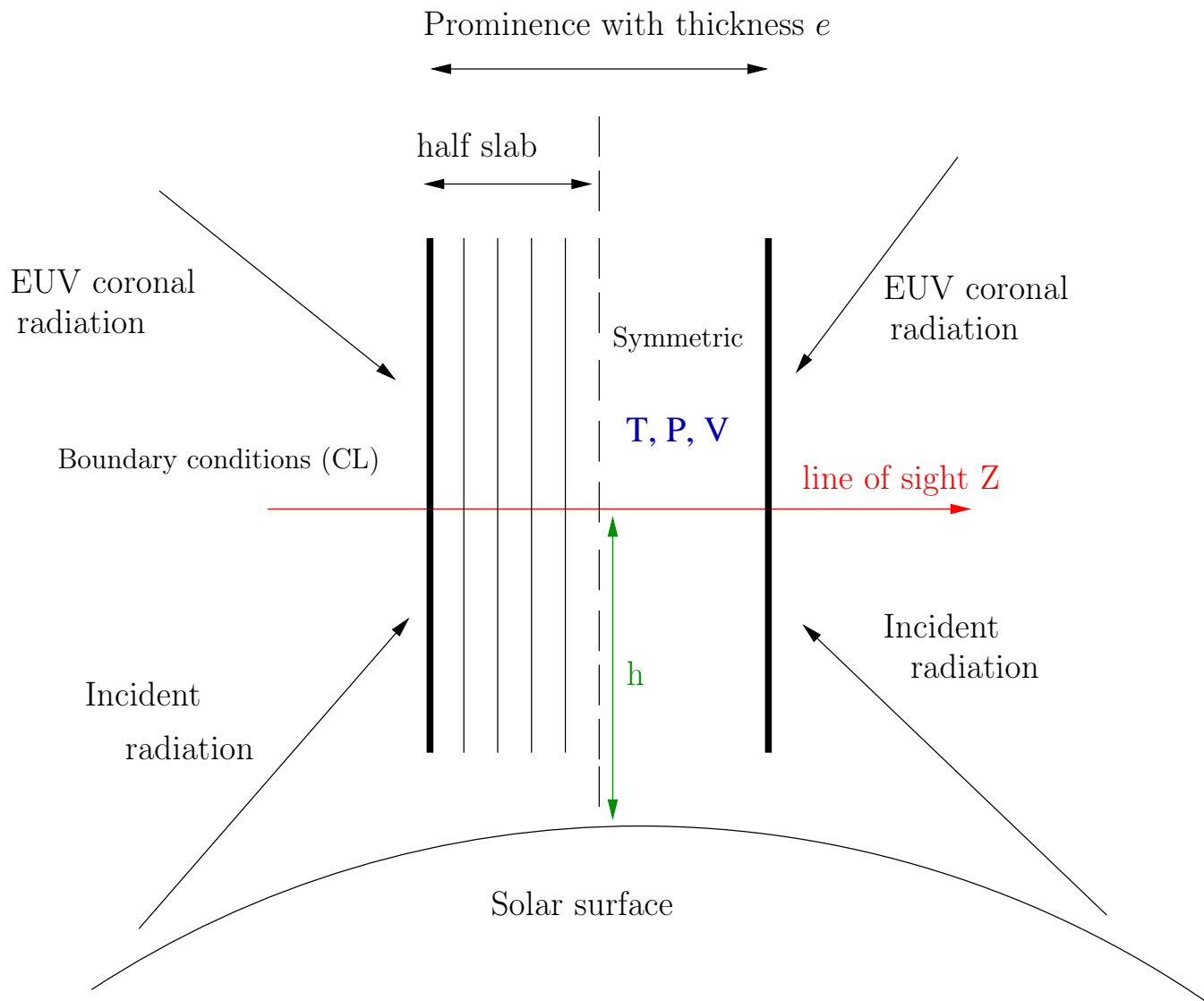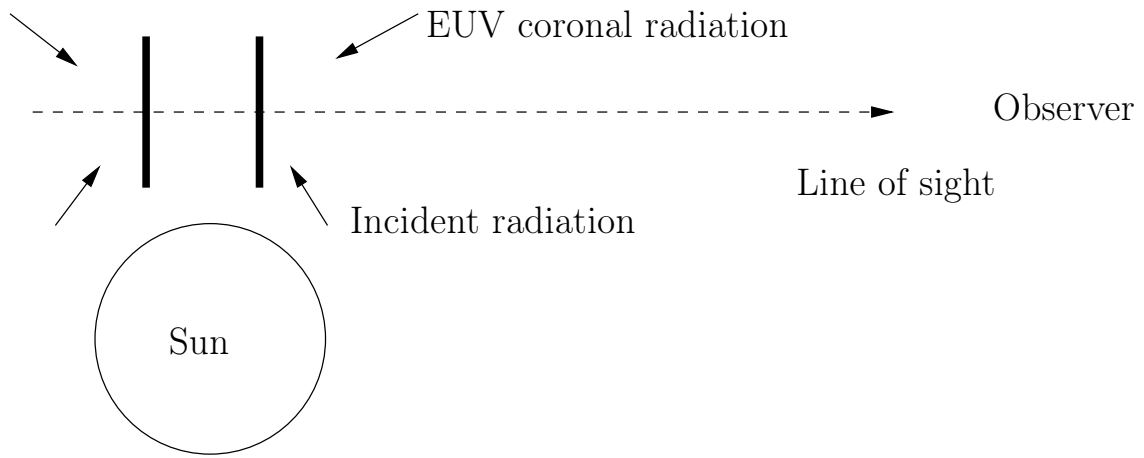
Position of the prominence with respect to the Sun and to the observer

Incident radiation

EUV coronal radiation

Sun

Observer

Line of sight

Incident radiation

EUV coronal radiation
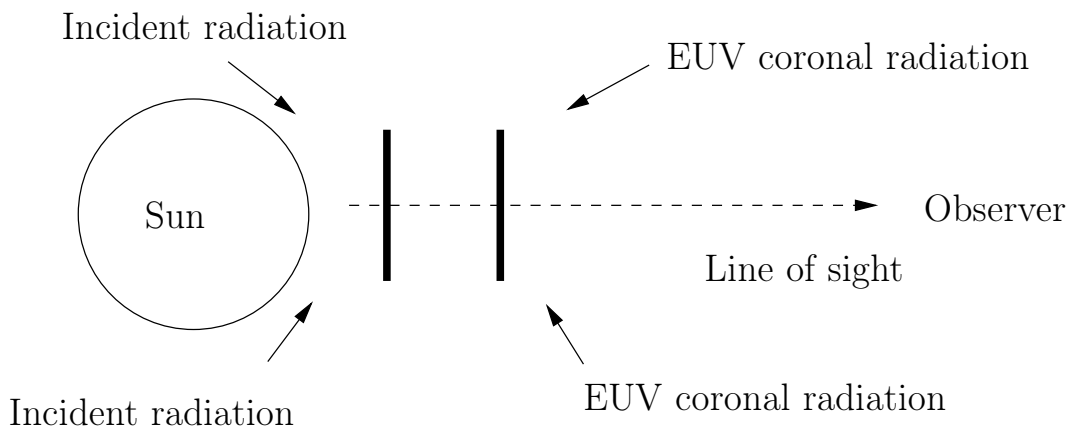
Position of the filament with respect to the Sun and to the observer

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 treshold level continuum, bound levels limit (∞). $NTT = NN \times (NN - 1)/2$ 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).

Transition	Lower level	Upper level	Transition name	Wavelength $\lambda(\text{Å})$
1	1	2	$Ly - \alpha$	1215
2	1	3	$Ly - \beta$	1025
3	2	3	$H - \alpha$	6564
4	1	4	$Ly - \gamma$	972
5	2	4	$H - \beta$	4862
6	3	4	$Pa - \alpha$	18756
7	1	5	$Ly - \delta$	949
8	2	5	$H - \gamma$	4341
9	3	5	$Pa - \beta$	12821
10	4	5	$Br - \alpha$	6563
11	1	6	$Ly - \epsilon$	973
12	2	6	$H - \delta$	4102
13	3	6	$Pa - \gamma$	10935
14	4	6	$Br - \beta$	4861
15	5	6	$Pf - \alpha$	7460
16	1	7	$Ly - 6$	931
17	2	7	$H - \epsilon$	3971
...	...	...	...	...
$NTAR + 1$	1	NN	Lyman continuum	911
$NTAR + 2$	2	NN	Balmer continuum	3645
...	...	...	...	...
$NTT =$	$NN - 1$	NN		

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 : $IR3$ ($\lambda = 8544\text{Å}$)

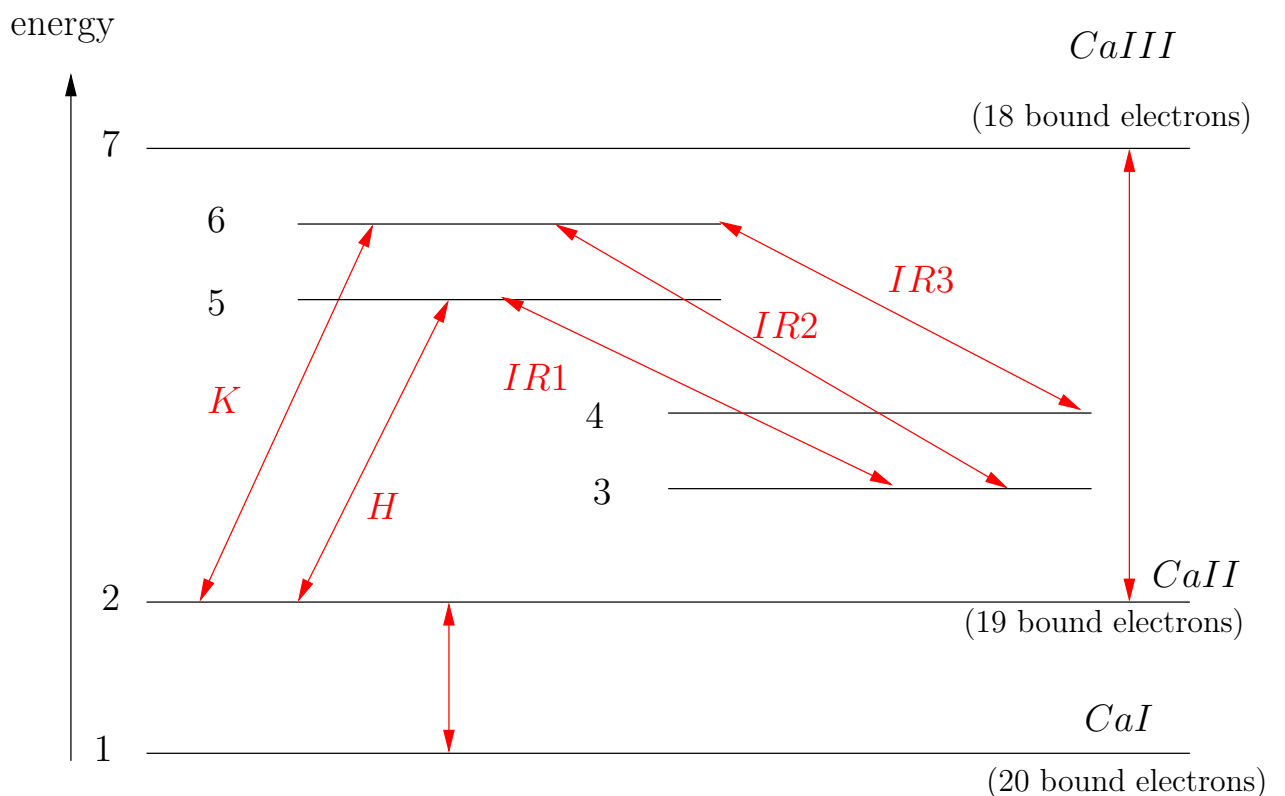- 2 to 7 : ionization of $CaII$ (between $CaII$ and $CaIII$ fundamental levels)

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

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:

$$N_j \sum_{j \neq i}^{n} P_{ji} = \sum_{j \neq i}^{n} N_i \ P_{ij} \tag{7.1}$$

For the calcium atom (see figure 6), $n = 7$.
The depopulation rate P_{ji} from level j is written as :

$$P_{ji} = A_{ji} + B_{ji} \bar{J}_{ij} + C_{ji} = R_{ji} + C_{ji} \tag{7.2}$$

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:

$$\bar{J}_{ij} = \int_{-\infty}^{+\infty} J_\nu \ \Phi_\nu \ d\nu \tag{7.3}$$

where J_ν is the mean intensity integrated over direction $\mu = \cos\theta$, θ being the angle between the light ray and the normal to the solar surface:

$$J_\nu = \frac{1}{2} \int_{-1}^{1} I_\nu(\mu) \ d\mu \tag{7.4}$$

Φ_ν is the normalized profile of the absorption coefficient $\left(\int \Phi_\nu \ d\nu = 1 \right)$.

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:

$$\sum_{j=1}^{n} N_j = N_T \tag{7.5}$$

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 ν_0) are coupled with the radiative transfer equation (7.6).
The intensity in the radiative transition is obtained by solving the transfer equation:

$$\mu \ \frac{dI_\nu}{d\tau_\nu} = I_\nu - S_\nu \tag{7.6}$$

τ_ν is the optical depth at frequency ν, and S_ν is the total source function defined by:

$$S_\nu = \frac{\epsilon_\nu}{\kappa_\nu},$$

where κ_ν is the absorption coefficient and ϵ_ν 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-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 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 $NXMOD = 46$ meshs. For a prominence model ($IVERT = 1$), the total number of meshs is $NZ = NXMOD = 46$ (half slab due to prominence symmetry, see figure 4). For a filament model ($IVERT = 0$), $NZ = 2\ NXMOD - 1 = 91$ (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
enddo
- output: line profiles given as data ("profil.dat")
- PSDEB, VISU21P, VISU21L : visualization programs (emergent intensities "profil.ps").

Input files for PROM7:

    $\star$ intinc.dat : hydrogen incident intensities

    $\star$ intica.dat : calcium incident intensities

    $\star$ tembri.dat : other lines of the hydrogen spectrum (Brightness temperatures)

    $\star$ 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:

    $\star$ resume.dat : iteration summary

    $\star$ profil.dat : line profiles given as data

    $\star$ profil.ps : line profiles as PostScript file

    $\star$ 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

- IVERT = 0: filament model (horizontal slab), IVERT=1: prominence model (vertical slab)

- NMDL: number of atmosphere models to be computed (isothermal and isobaric)

- NXMOD: number of meshs in the half slab

- NZ: total number of meshs

- NFR: number of frequencies in a line

- NMU: number of directions $\mu = \cos\theta$, where θ 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 TAB (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 meshs), IOPMRU = 0: all the redistribution matrices are computed for each transition (the same matrix is used for all meshs)

- 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 μ (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

- LYLI: 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 (AJI: Einstein A coefficient, BIJ and BJI: 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 ($FADIR$: dilution factors for lines, $FADIC$: dilution factors for continua)

- COLHCF: boundary conditions for hydrogen (intensities)

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

- INITR1: 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 presure 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, RKI

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
  - – PROFLI: 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 meshs), $NTAR$ (number of lines), $NTAC$ (number of continua), NFR (number of frequencies in a line), $NFRC$ (number of frequencies in a continuum)

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

INIHYV3

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 $\omega_i B_{ij} = \omega_j B_{ji}$, where ω_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:

$$
\begin{aligned}
S_e(n, n') = {}&(8kT/\pi m)^{1/2} \frac{2n^2}{x}\, \pi\, a_0^2\, y^2 \left(A_{nn'} \left[\left(\frac{1}{y} + \frac{1}{2} \right) E_1(y) - \left(\frac{1}{z} + \frac{1}{2} \right) E_1(z) \right] \right) \\
&+ (8kT/\pi m)^{1/2} \frac{2n^2}{x}\, \pi\, a_0^2\, y^2 \left(\left[B_{nn'} - A_{nn'}\, \ln \frac{2n^2}{x} \right] \left[\frac{1}{y} E_2(y) - \frac{1}{z} E_2(z) \right] \right)
\end{aligned}
\tag{9.1}
$$

$E_i(z) = \int_1^\infty e^{-zt}\, t^{-i}\, dt$ is called Exponential integral of order i ($i = 0, 1, 2, ...$).
m denotes the electron mass and $a_0 = 0.5292\ 10^{-8}\ cm$ the Bohr radius.

19

Here and below, E_n denotes level energy of n for hydrogen. We obtain:

$$y = (E_{n'} - E_n)/kT,$$
$$z = r_{nn'} + y,$$
$$x = 1 - (n/n')^2,$$
$$B_{nn'} = \frac{4n^4}{n'^3} \ x^{-2} \ (1 + \frac{4}{3}x^{-1} + b_n \ x^{-2}),$$

$$b_n = n^{-1}(4 - 18.63n^{-1} + 36.24n^{-2} - 28.09n^{-3}), \quad n \geq 2,$$
$$A_{nn'} = 2n^2 \ x^{-1} \ f_{nn'},$$

$$f_{nn'} = \frac{32}{3\sqrt{3} \ \pi} \frac{n}{n'^3} \ x^{-3} \ g(n, x),$$

$$g(n, x) = g_0(n) + g_1(n) \ x^{-1} + g_2(n) \ x^{-2},$$
$$r_{nn'} = r_n \ x,$$
$$r_n = 1.94n^{-1.57}$$

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

	$n = 1$	$n = 2$	$n \geq 3$
$g_0(n)$	1.11330	1.0785	$0.9935 + 0.2328n^{-1} - 0.1296n^{-2}$
$g_1(n)$	-0.4059	-0.2319	$-n^{-1}(0.6282 - 0.5598n^{-1} + 0.5299n^{-2})$
$g_2(n)$	0.07014	0.02947	$n^{-2}(0.3887 - 1.181n^{-1} + 1.470n^{-2})$

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:

$$S_i(n) = (8kT/\pi m)^{1/2} \ 2n^2 \ \pi \ a_0^2 \ y_n^2 \ A_n \left[\frac{1}{y_n}E_1(y) - \frac{1}{z_n}E_1(z_n) \right]$$

$$+ (8kT/\pi m)^{1/2} \ 2n^2 \ \pi \ a_0^2 \ y_n^2 \ (B_n - A_n \ln 2n^2)[\zeta(y_n) - \zeta(z_n)],$$

$$(9.2)$$

where m is the electron mass and

$$y_n = I_n/kT,$$
$$z_n = r_n + I_n/kT,$$

$$\zeta(t) = E_0(t) - 2E_1(t) + E_2(t)$$

where 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 Φ_ν. Profile line is renormalized (intensity): $GIOM = \int J_\nu\ \phi_\nu\ d\nu$.

For continua: lower boundary condition $FIIC$ is null for prominence models and is equal to $2\,B_\nu \times FADIC$ for filament models. $FADIC$ is the dilution factor dilution (see **INTALT** subroutine) and B_ν is the Planck function. Upper boundary condition $FISC$ is equal to $B_\nu \times FADIC$ for prominence models and null for filament models.

Inputs: $IVERT$, NZ, NN, NTT, $NTRD$, $NTRC$, NFR, $NFRC$, $NFIMX$, $ITRD$, $ICTR$, $NINF$, $NSUP$, 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 $FADIC$. 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 α line (H)

MARALA : computation of the redistribution matrix for Ly α 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: RDMAT (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

23

used for statistical equilibrium).

HCONTI uses the following subroutines:

CSIETA: computation of $CSI0$ and $ETA0$ which are for continua, the equivalents of ϵ 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 fonctions S. We use Feautrier method and variable Eddington factors

NOVFEV: computes new Eddington factors (outputs : $FEVK$ et $FEVL$) from source fonctions ([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, $IVERT$, 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 meshs and source functions are computed (outputs : main intensity $GIBAR$ and intensity inside the slab GI. We deduce source fonction 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, $IVERT$, 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 fonction 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 ($TSLAB$, $PSLAB$, $EPST$, $VTUR$, 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:

26

PROFSC: see ABSCON subroutine

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

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

Inputs for HYTOCA: $LYLI$, $IVERT$, 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

ECRITAU: prints collisional transiiton 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°K, V = 5 km.s⁻¹, h = 10000 km, e = 200 km, P = 0.5 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.
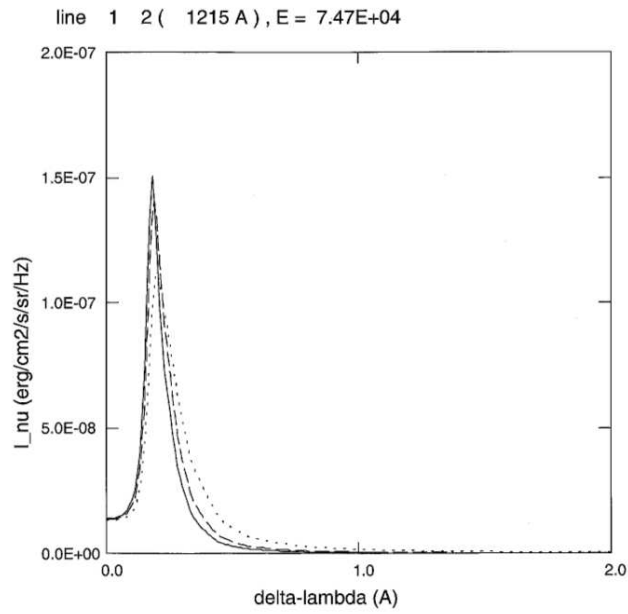
10.1 Hydrogen

line 1 2 (1215 A) , E = 7.47E+04

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

line 1 3 (1025 A) , E = 3.83E+02
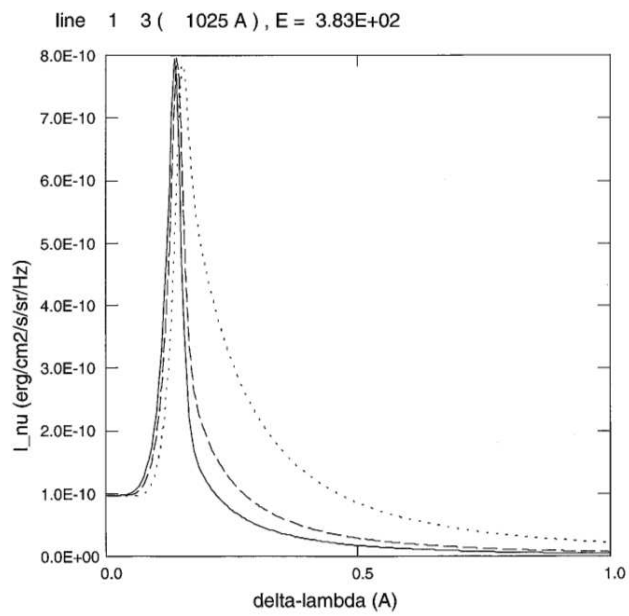
Figure 8: Half-profile of $L\beta$ line at 1025Å

line 2 3 (6564 A), E = 1.67E+05
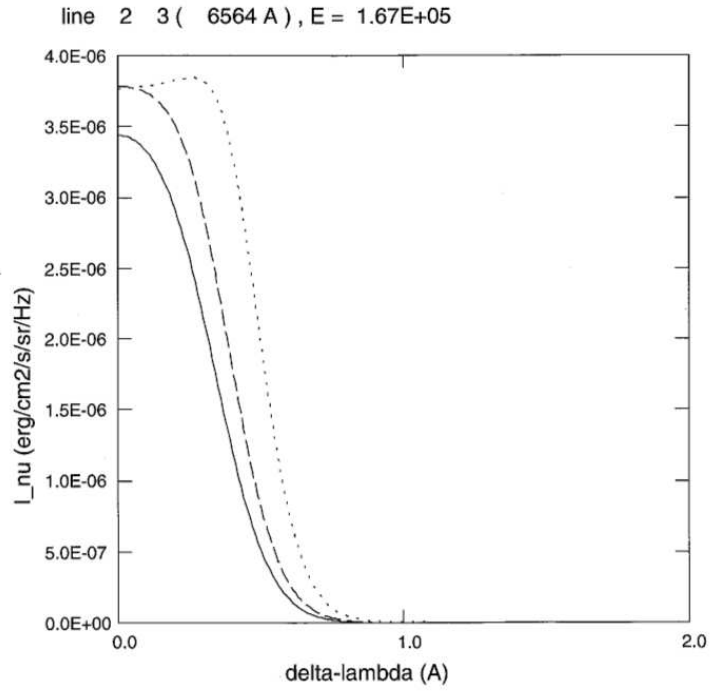
Figure 9: Half-profile of $H\alpha$ line at 6564Å

line 1 4 (972 A), E = 7.97E+01
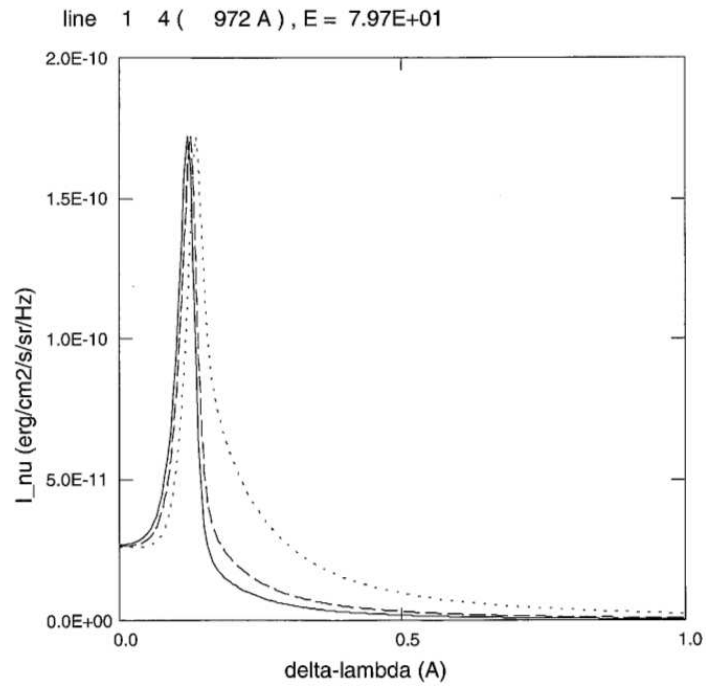
Figure 10: Half-profile of $L\gamma$ line at 972Å

30

line 2 4 (4862 A) , E = 2.30E+04
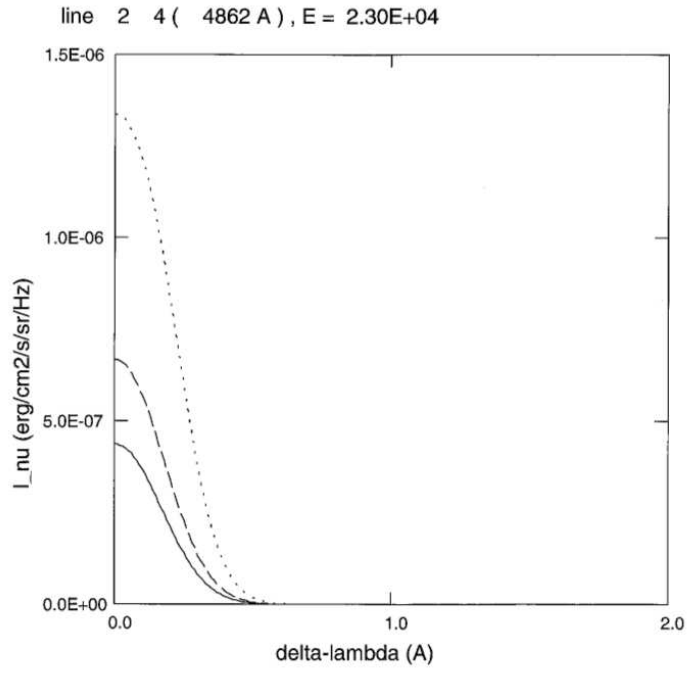
Figure 11: Half-profile of $H\beta$ line at 4862Å

line 3 4 (18756 A) , E = 6.93E+03
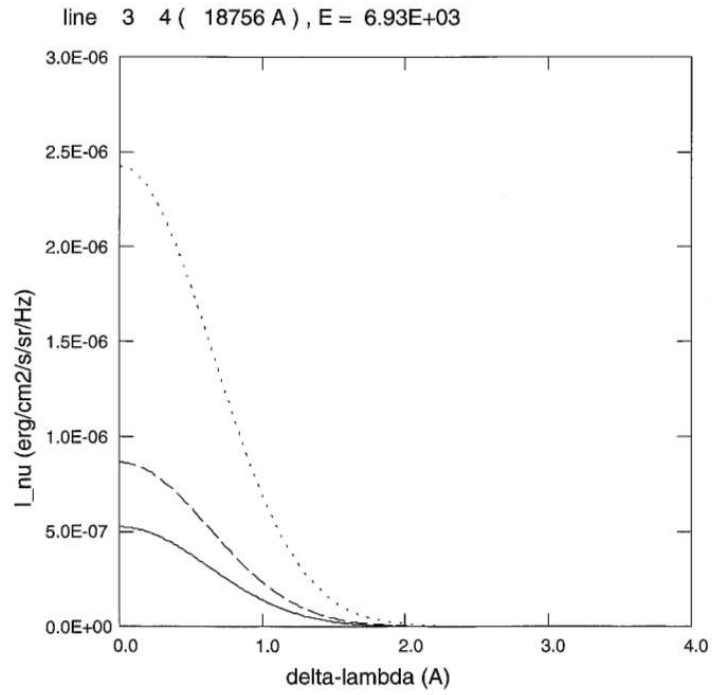
Figure 12: Half-profile of $Pa - \alpha$ line at 18756Å

31

line 2   5 (4341 A) , E = 7.73E+03
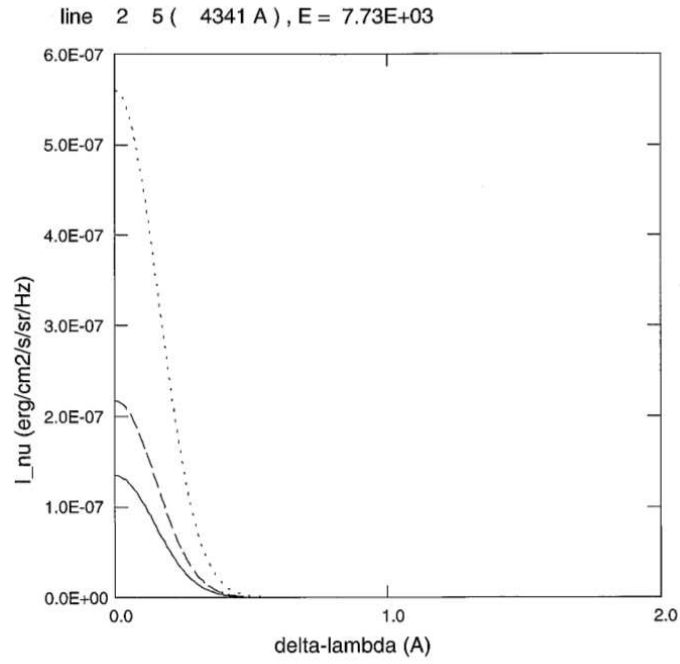
Figure 13: Half-profile of $H\gamma$ line at 4341Å

line 3   5 (12821 A) , E = 2.35E+03
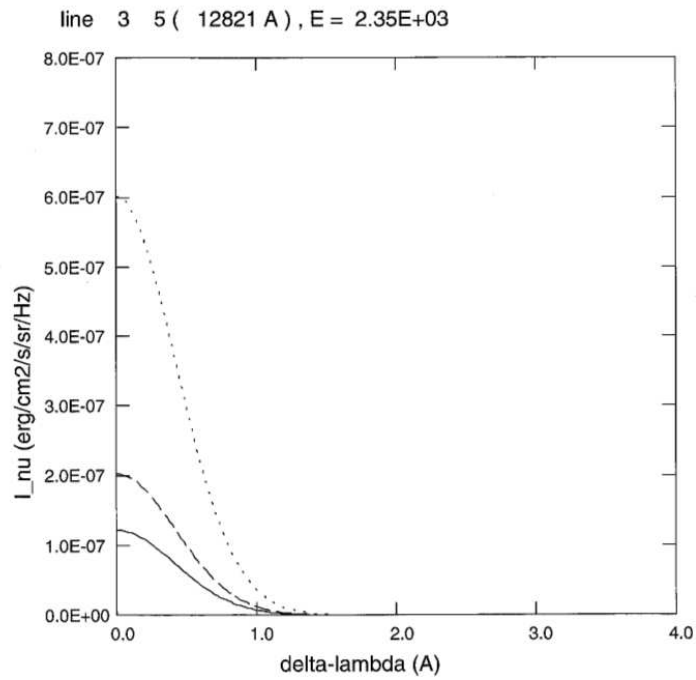
Figure 14: Half-profile of $Pa - \beta$ line at 12821Å

32

line   2   6 (4102 A) , E = 4.22E+03
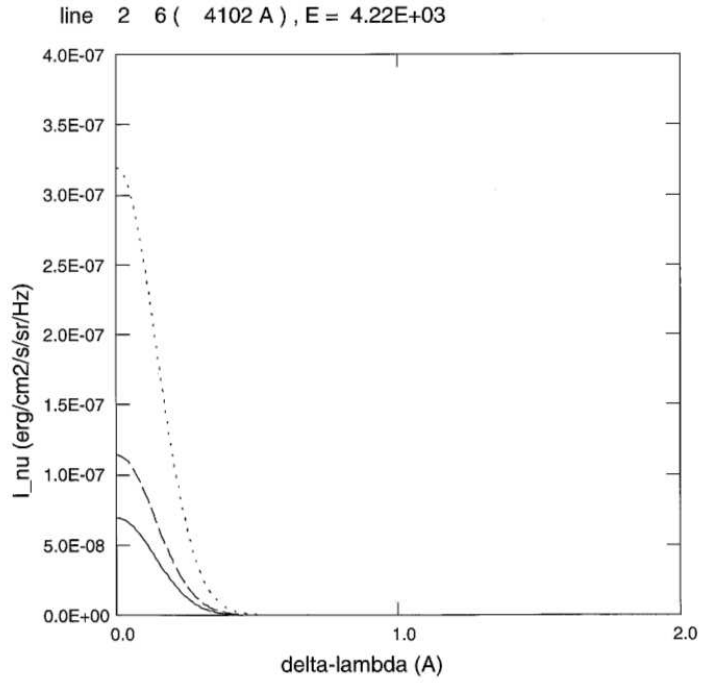
Figure 15: Half-profile of $H\delta$ line at 4102Å

line   2   7 (3971 A) , E = 2.14E+03
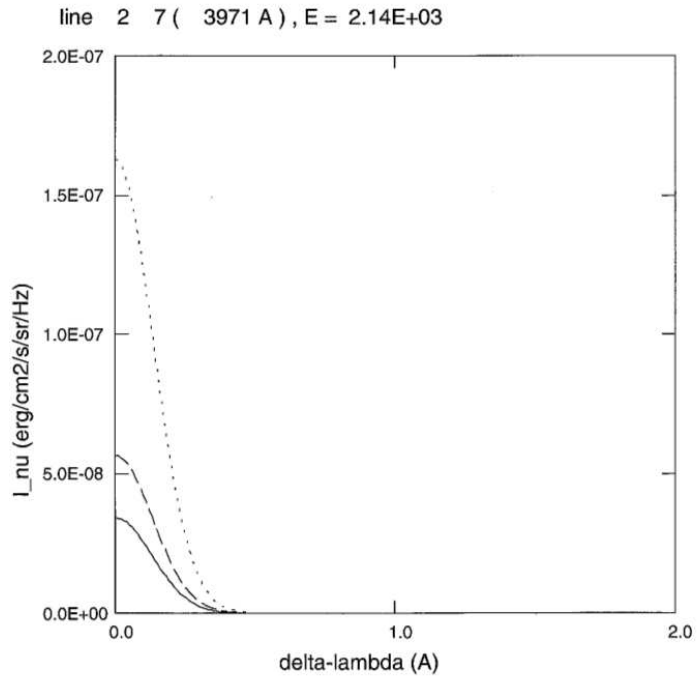
Figure 16: Half-profile of $H\epsilon$ line at 3971Å

33
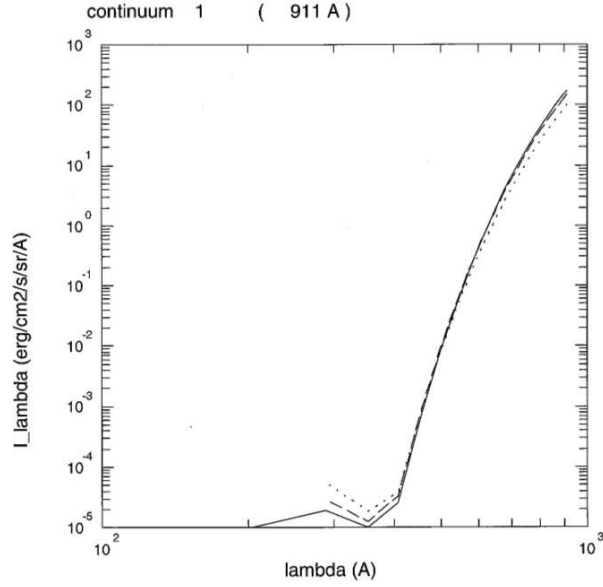
Figure 17: Continuum sprectrum at 911Å. Note the change of intensity unit

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.
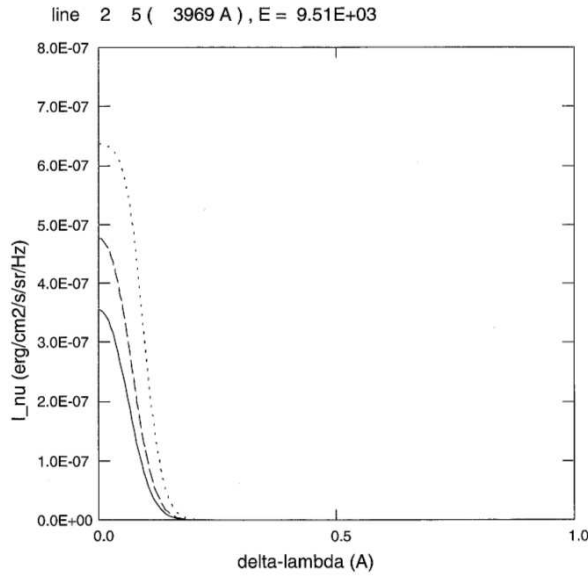
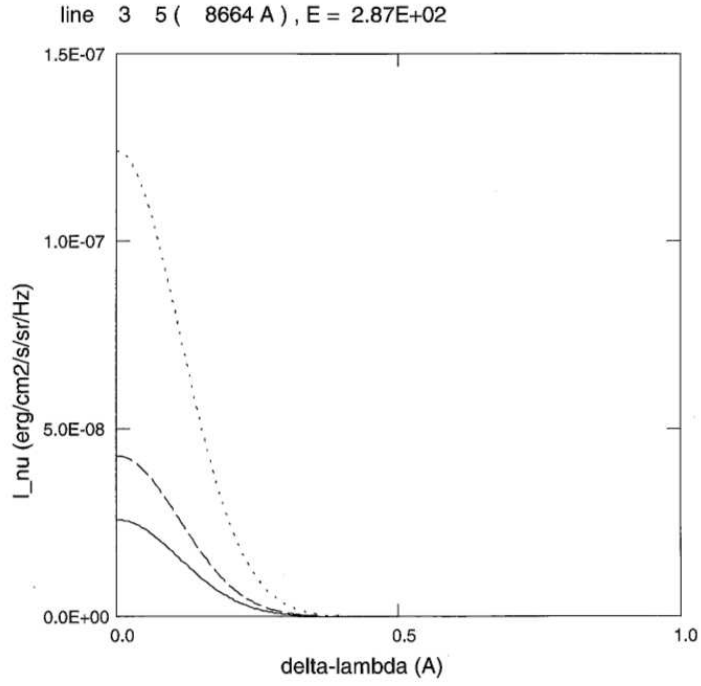Figure 18: Half-profile of H line at 3969Å for $CaII$

34

line   3   5 (8664 A) , E = 2.87E+02

Figure 19: Half-profile of $IR1$ line at 8664Å for $CaII$

line   2   6 (3934 A) , E = 1.75E+04
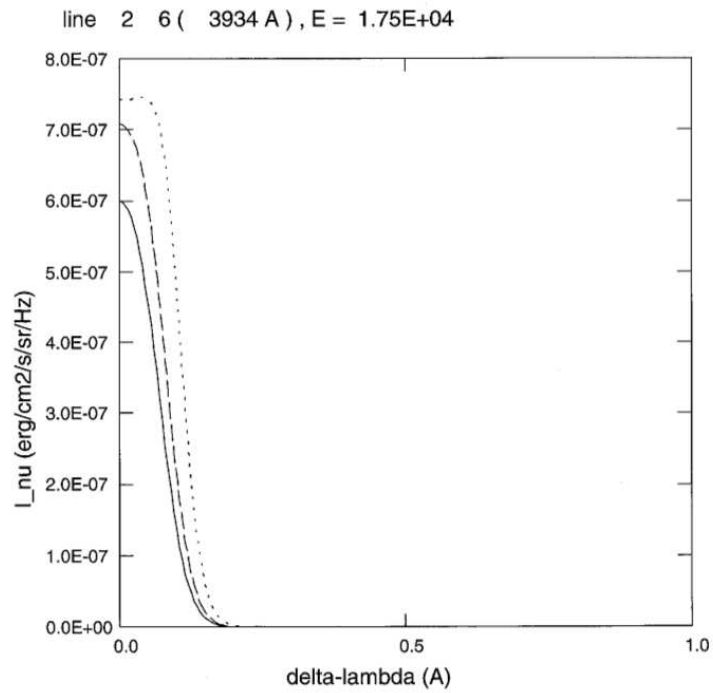
Figure 20: Half-profile of K line at 3934Å for $CaII$

line 3 6 (8500 A) , E = 7.09E+01
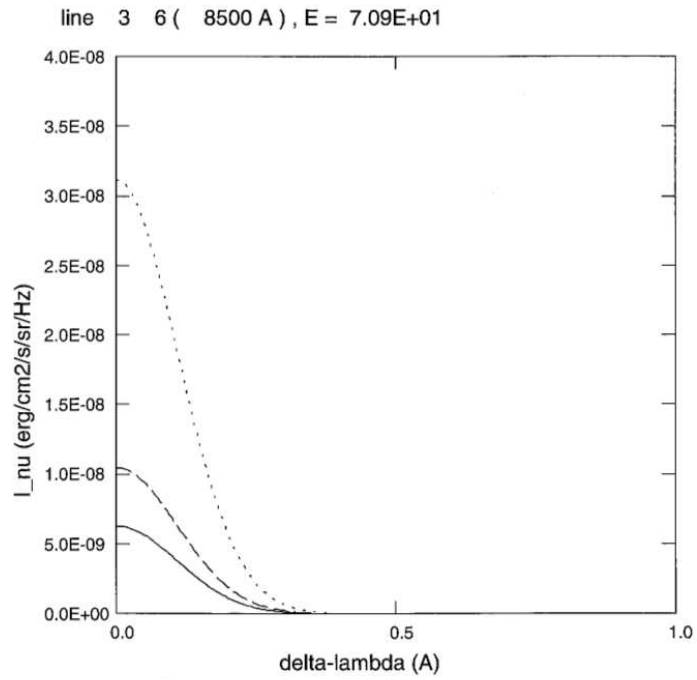
Figure 21: Half-profile of $IR2$ line at 8500Å for $CaII$
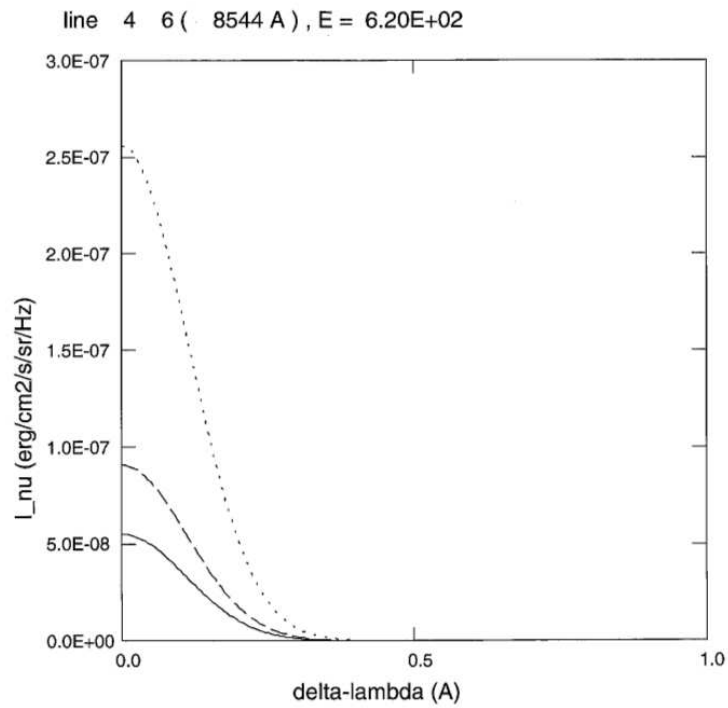
line 4 6 (8544 A) , E = 6.20E+02

Figure 22: Half-profile of $IR3$ line at 8544Å for $CaII$

36

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 ouput 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°K, V = 5 km.s^{-1}, h = 10000 km, e = 200 km, P = 0.01 dyn.cm^{-2}

- T = 8000°K, V = 5 km.s^{-1}, h = 10000 km, e = 200 km, P = 0.1 dyn.cm^{-2}

- T = 10000°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 $s \sim 13\ mins$, because in filament case, calculations are made in the entire slab and not in the half slab as for prominence case.

13   Acknowledgements

28th September 2015
M. C-Y

References

[1] C.W. Allen. *Astrophysical quantities*. The Athlone Press, University of London, 1973.

[2] M. Arnaud and R. Rothenflug. An updated evaluation of recombination and ionization rates. *A&A suppl. Ser.*, 60:425–457, 1985.

[3] L.H. Auer and D. Mihalas. On the use of variable Eddington factors in Non-LTE stellar atmospheres computations. *Mon. Not. R. astr. Soc*, 149:65–74, 1970.

[4] Eugene H. Avrett. *Introduction to Non-LTE radiative transfer and atmospheric modeling*. Lecture notes, 2008.

[5] S. Chandrasekhar. *Radiative transfer*. Dover Publications, 1960.

[6] CHIANTI Database. George Mason University (USA) and University of Michigan (USA) and University of Cambridge (UK). *http://www.chiantidatabase.org/*, Mai 2014.

[7] K.P. Dere, E. Landi, H.E. Mason, B.C. Monsignori Fossi, and P.R. Young. CHIANTI - an atomic database for emission lines: I. Wavelengths greater than 50a. *A&A suppl. Ser.*, 125:149–173, 1997.

[8] O. Gingerich. Review of Opacity Calculations. *Proceedings of the First Harvard-Smithsonian Conference on Stellar Atmospheres*, 167:1–25, 1964.

[9] P. Gouttebroze and P. Heinzel. Calcium to hydrogen line ratios in solar prominences. *A&A*, 385:273–280, 2002.

[10] P. Gouttebroze, P. Heinzel, and J.-C. Vial. The hydrogen spectrum of model prominences. *A&A Suppl. Ser.*, 99:513–543, 1993.

[11] P. Gouttebroze and N. Labrosse. A ready-made code for the computation of prominence NLTE medels. *Solar Physics*, 196:349–355, 2000.

[12] Pierre Gouttebroze. *Formation des raies spectrales et oscillations dans la chromosphère solaire*. Thèse d'Etat, Université Paris 7, 1980.

[13] I. Hubeny and D. Mihalas. *Theory of Stellar Atmospheres : An introduction to Astrophysical Non-equilibrium Quantitative Spectroscopic Analysis*. Princeton University Press, 2015.

[14] J.T. Jefferies. *Spectral line formation*. Blaisdell, 1968.

[15] L.C. Johnson. Approximation for collisional and radiative transition rates in atomic hydrogen. *A&A*, 174:227–236, 1972.

[16] Nicolas Labrosse. *Modélisation du spectre de l'hélium dans les protubérances solaires*. PhD thesis, Université Paris XI Orsay, 2001.

[17] P. Lemaire, P. Gouttebroze, J.-C. Vial, and G. E. Artzner. Physical properties of the solar chromosphere deduced from optically thick lines: I. Observations, data reduction, and modelling of an average plage. *A&A*, 103:160–176, 1981.

[18] J. Oxenius. *Kinetic Theory of Particles and Photons. Theoretical Foundations of Non-LTE Plasma Spectroscopy.* Springer-Verlag, 1986.

[19] G. Peach. A general formula for the calculation of absorption cross sections for free-free trabsitions in the field of positive ions. *Royal Astronomical Society*, 130:361–377, 1964.

[20] C. Pecker-Wimel. *Introduction à la spectroscopie des plasmas.* Gordon and Breach, 1966.

[21] R.J. Rutten. *Radiative transfer in stellar atmospheres.* 2003.

[22] E. Schatzman. *Astrophysique.* Masson et Cie, 1963.

[23] J.E. Vernazza, E. H. Avrett, and R. Loeser. Structure of the Solar chromosphere; ii. The underlying photosphere and temperature-minimum region. *ApJS*, 30:1–60, 1976.