

USER GUIDE

PRODOP : Non-LTE radiative transfer in solar prominences and filaments (1D transfer with vertical velocity field)

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<https://idoc.ias.u-psud.fr/MEDOC/Radiative%20transfer%20codes>

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1 Introduction

The original version of PRODOP code, written in Fortran 77/90 by P. Gouttebroze ([5], [6], [7], [9]), describes non-LTE radiative transfer (1D) in solar prominences and filaments, using partial frequency redistribution for resonance lines of hydrogen, calcium and helium. The code includes a vertical velocity field. The problem consists in solving a set of equations including the ionization equilibrium of the most abundant elements, the statistical equilibrium of level populations (for hydrogen atom and possibly other atoms, here calcium, helium), non-LTE radiative transfer in studied transitions.

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:

- either isothermal and isobaric, defined by temperature, T , pressure, P , microturbulent velocity, V_T , thickness, e , altitude, h and velocity V (velocity of matter, which moves vertically in block),
- or have variable parameters across the solar structure.

For each model of atmosphere, 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 and helium lines. These lines (intensity, profile) are used to diagnose solar prominences and filaments through comparison with observations.

Mg II resonance lines (2796Å et 2803Å, called k and h) and subordinate lines (2791Å and 2798Å) processing was added to the original version of PRODOP.

PRODOP code, adapted to **gfortran** compiler, is available from MEDOC website (1D): <https://idoc.ias.u-psud.fr/MEDOC/Radiative%20transfer%20codes>

In the following sections, we will explain in details PRODOP code (hydrogn, calcium, helium and magnesium): modeling, implemented equations, algorithm, numerical methods, etc.

2 Description of PRODOP code

Nature of the physical problem: NLTE radiative transfer (1D transfer with vertical velocity field) in solar prominences and filaments (HI, CaII, HeI, HeII, MgII lines)

Method of solution: Feautrier method with variable Eddington factors

Other relevant information:

- The atmosphere models considered here are :

* either isothermal and isobaric defined by T , P , V_T , e , h , V (temperature, pressure, microturbulent velocity, thickness, altitude, bulk velocity),

* or have variable parameters across the solar structure

- Partial frequency redistribution (PRD) is used for resonance lines of hydrogen, calcium, helium and magnesium, 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%20transfer%20codes>

Computer(s) on which program has been tested: PC

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

Programming language used: Adapted in Fortran 90 for **gfortran** and tested (by M. Chaneyook)

Status: Stable

Accessibility: open (MEDOC)

No. of code lines in combined program and test deck: $\sim 10\,000$

Typical running time: < 1 min (PC with 4 processors (2.67GHz)) for 2 atmosphere (with fixed parameters) models (prominence)

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

- N. Labrosse, P. Gouttebroze and J.-C. Vial, "Effect of motions in prominences on the helium resonance lines in the extreme ultraviolet", *A&A*, 463, 1171-1179, 2007

- N. Labrosse, P. Gouttebroze and J.-C. Vial, "Diagnostics of active prominences", *The Physics of Chromospheric Plasmas ASP Conference Series*, Vol. 368, 2007

3 Algorithm

The figure 1 describes the algorithm of PRODOP code.

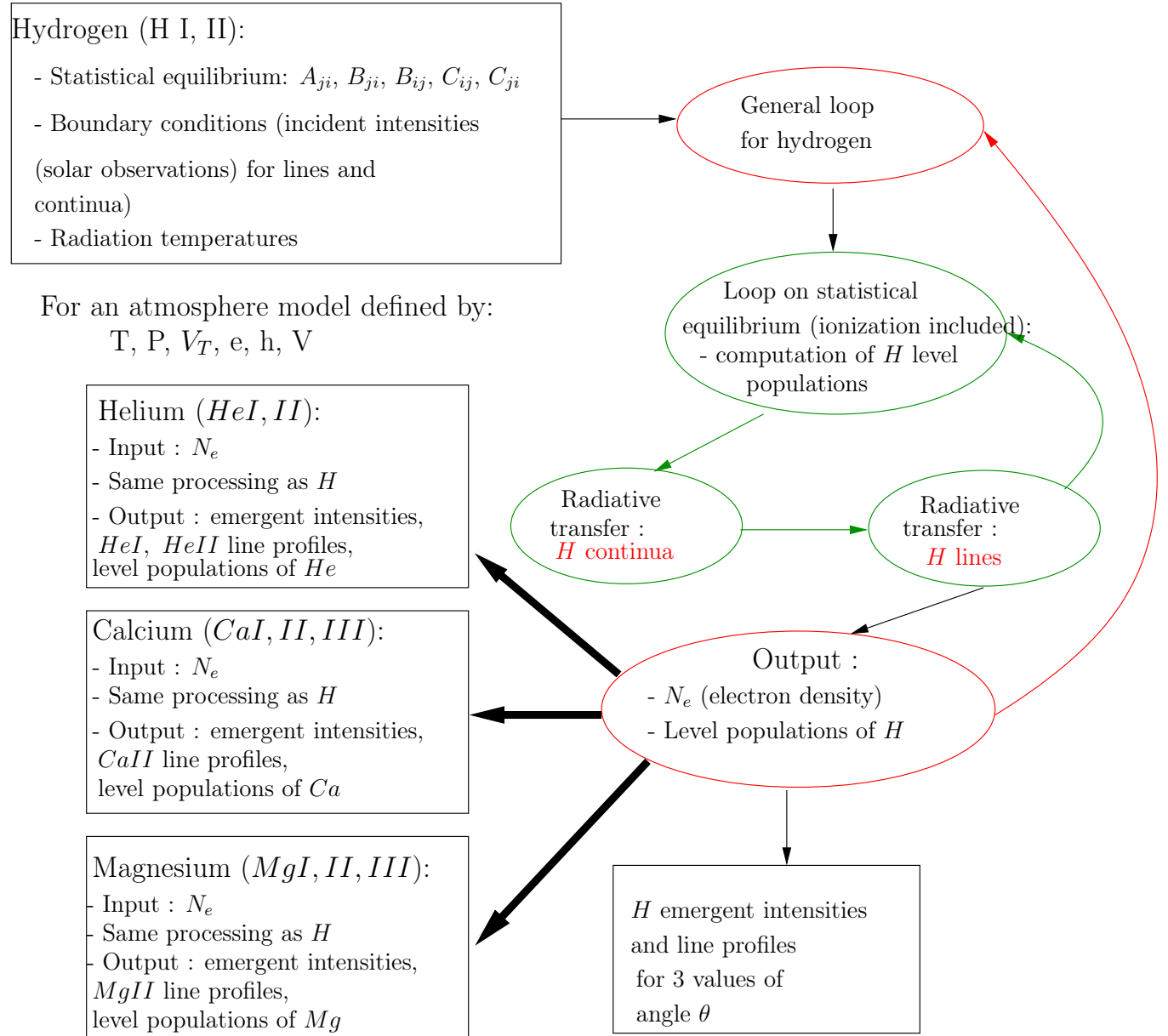


Figure 1: Algorithm of PRODOP code

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

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

The first step of PRODOP code is to calculate the electron density which will be used in the formation of calcium, helium and magnesium 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 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 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 Ca II lines. To study a Ca II line, we need to know all the electronic states of calcium ions. There are only Ca I, Ca II and Ca III ions at the temperature of prominences or filaments, the others being negligible. We can do now radiative transfer in Ca II lines to obtain Ca II emergent spectrum for many values of angle θ and Ca I, Ca II and Ca III level populations. The same process is applied for helium and magnesium.

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 plane-parallel slab with thickness e , standing vertically above the solar surface (at altitude h) and irradiated on both sides by the Sun. It is a 1D representation. Each side of this symmetrical model is illuminated by incident radiation from the photosphere, chromosphere and solar corona. This radiation field is very important since it determines the boundary conditions for the resolution of the transfer equations (see paragraph 7). Inside the prominence, the initial condition is defined by 3 physical parameters: electronic temperature, T , pressure, P , microturbulence velocity, V_T . The prominence moves vertically with 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 (see figure 3) but not in the filament model.



Figure 2: Erupting solar prominence observed by SDO/AIA, at 304Å and 171Å wavelengths, 2012/08/30

5 Bound-Free and Bound-Bound transitions

The transitions used in PRODOP 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 for instance.

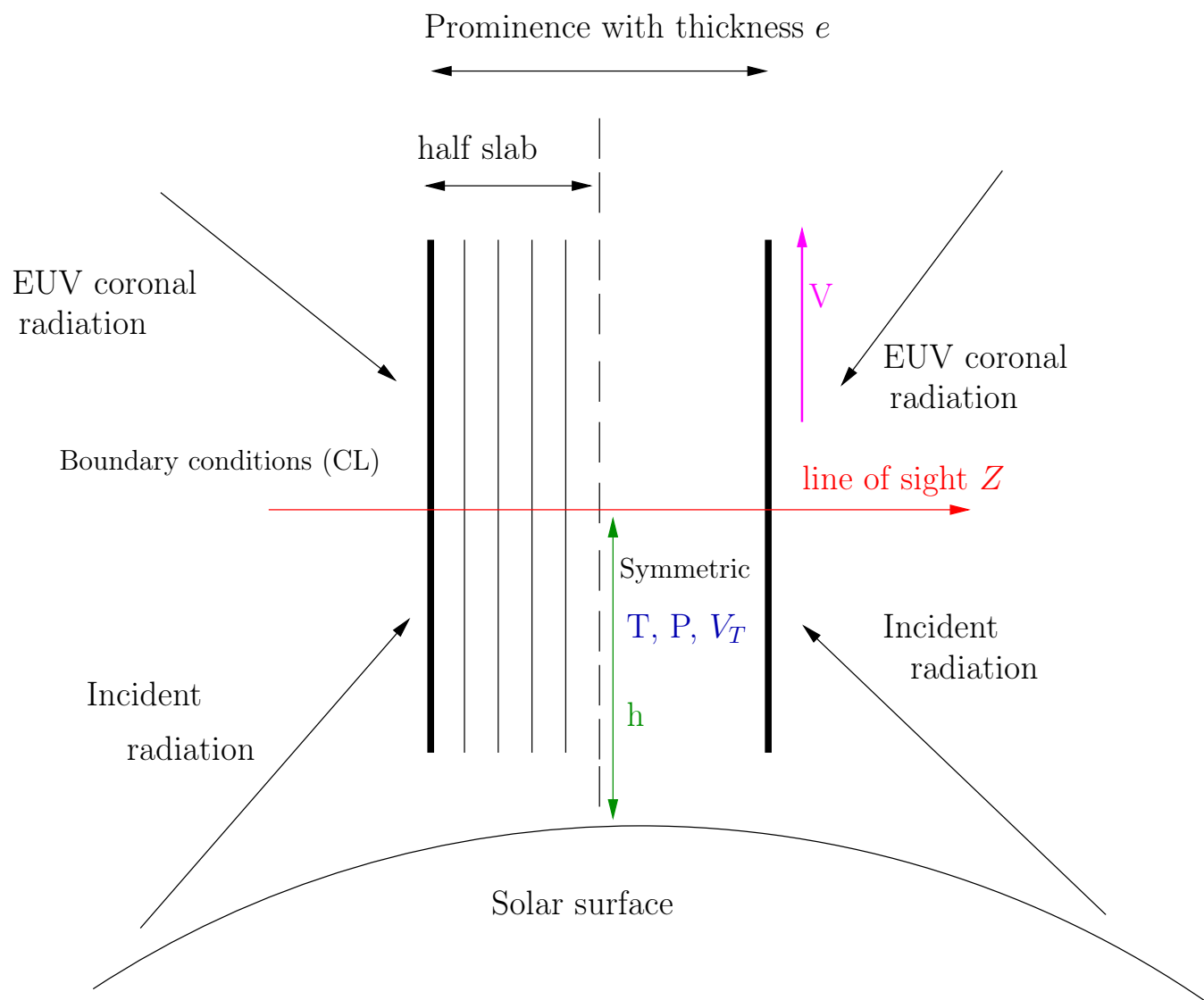
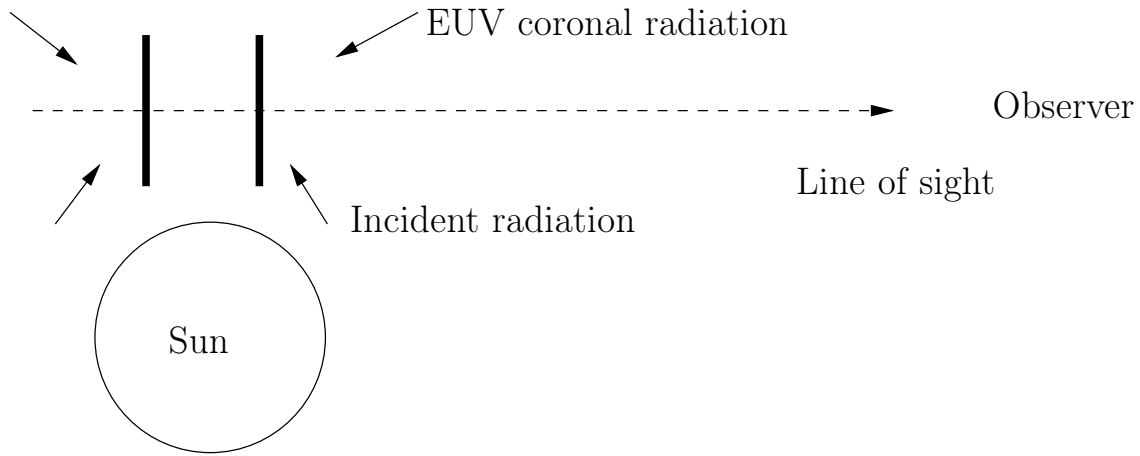
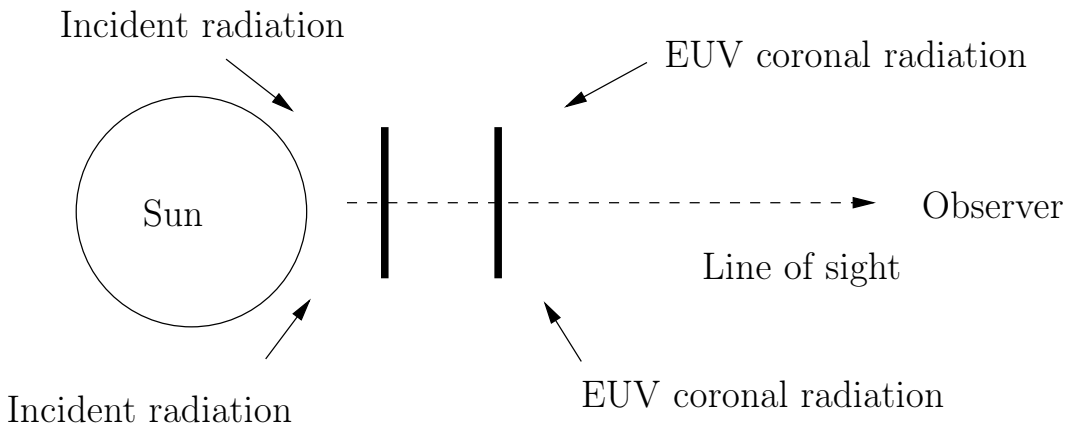


Figure 3: Prominence model



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

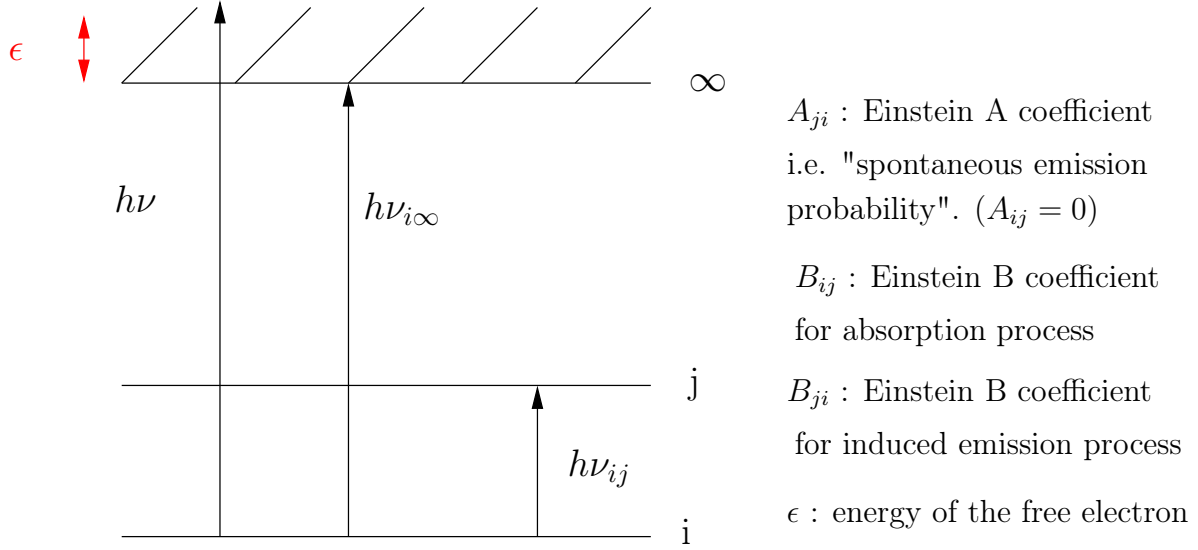


Figure 5: Transition types used in PRODOP

6 Atomic data

In this section we describe the atomic structure of the following atoms: hydrogen, calcium, helium and magnesium. For each atomic element, NN is the number of energy levels, including the threshold 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).

6.1 Hydrogen

The transitions for hydrogen are summarized in Table 1. In PRODOP code, $NN = 21$ (20 levels and 1 continuum), $NTAC = 20$, $NTT = 210$, $NTAR = 190$.

Transition NT	Lower level NI	Upper level NS	Transition name	Wavelength $\lambda(\text{\AA})$
1	1	2	<i>Ly</i> α	1215
2	1	3	<i>Ly</i> β	1025
3	2	3	<i>H</i> α	6564
4	1	4	<i>Ly</i> γ	972
5	2	4	<i>H</i> β	4862
6	3	4	<i>Pa</i> α	18756
7	1	5	<i>Ly</i> δ	949
8	2	5	<i>H</i> γ	4341
9	3	5	<i>Pa</i> β	12821
10	4	5	<i>Br</i> α	40522
11	1	6	<i>Ly</i> ϵ	937
12	2	6	<i>H</i> δ	4102
13	3	6	<i>Pa</i> γ	10935
14	4	6	<i>Br</i> β	26259
15	5	6	<i>Pf</i> α	7460
16	1	7	<i>Ly</i> 7	931
17	2	7	<i>H</i> ϵ	3971
...
<i>NTAR</i> + 1	1	<i>NN</i>	Lyman Continuum	911
<i>NTAR</i> + 2	2	<i>NN</i>	Balmer continuum	3645
...
<i>NTT</i>	<i>NN</i> - 1	<i>NN</i>		

Table 1: Main transitions for hydrogen

6.2 Calcium

For calcium, 7 levels and 5 radiative transitions (see figure 6). More particularly, these are the absorption and emission transitions described in the table 2.

In PRODOP code, $NN = 7$ (5 levels of Ca II, 1 level of Ca I (fundamental state), 1 level of Ca III (fundamental state)), $NTT = 21$ (total number of transitions), $NTC = 16$ (number of collisional transitions), $NTRC = 6$ (number of “continua” i.e. bound-free transitions), $NTRD = 5$ (number of lines).

For more details, see the description of CAIP subroutine in section 9.3.

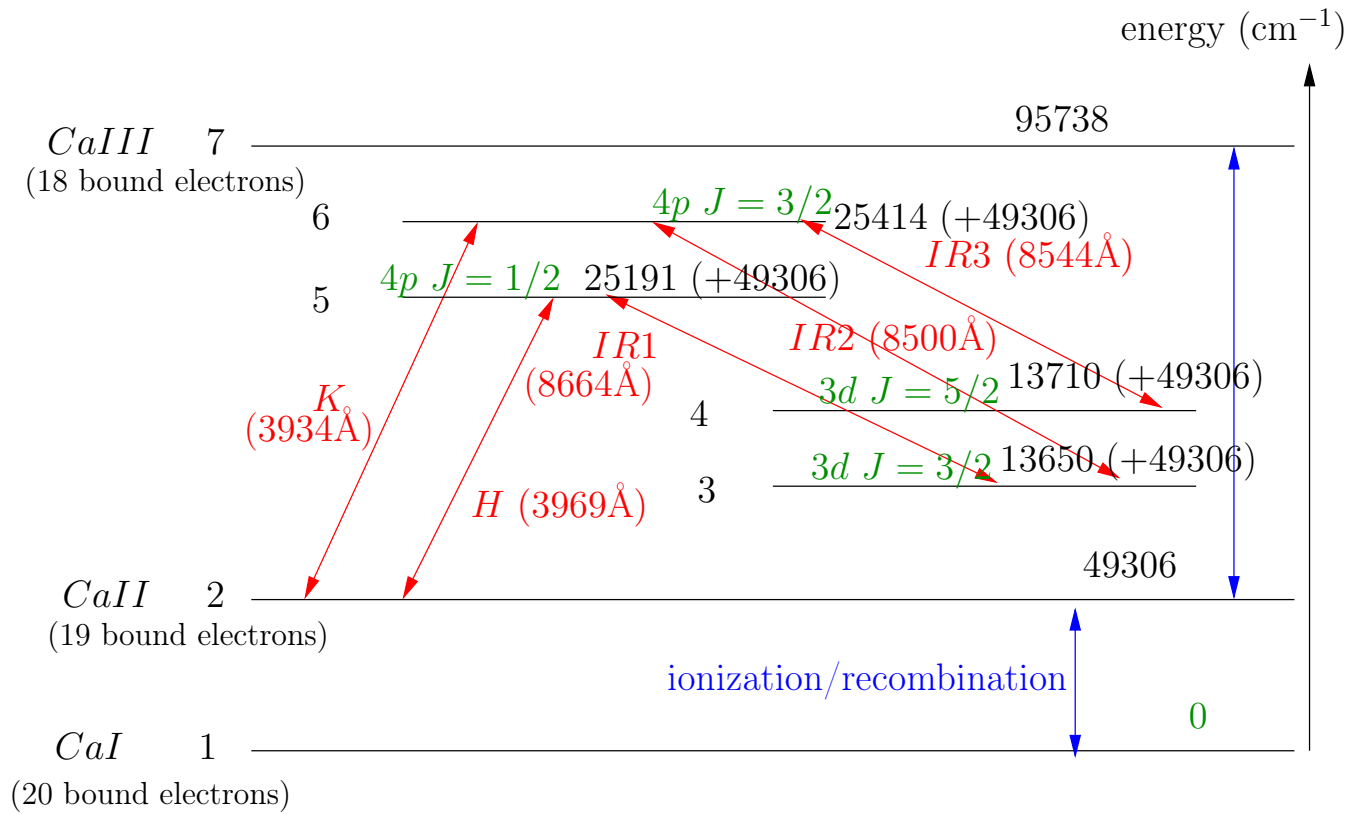


Figure 6: Description of calcium levels (figure is not to scale) - 5 radiative transitions (in red). $\omega = 2J + 1$ is the statistical weight of the considered level

Transition NT	Lower level NI	Upper level NS	Transition name
1	1	2	1st continuum : ionization from the fundamental state of <i>CaI</i> to the fundamental state of <i>CaII</i>
2	1	3	ionization : ignored
3	2	3	excitation
4	1	4	ionization : ignored
5	2	4	excitation
6	3	4	excitation
7	1	5	ionization : ignored
8	2	5	raie <i>H</i> ($\lambda = 3969\text{\AA}$) : excitation
9	3	5	<i>IR1</i> ($\lambda = 8664\text{\AA}$) : excitation
10	4	5	excitation : forbidden line
11	1	6	ionization : ignored
12	2	6	<i>K</i> line ($\lambda = 3934\text{\AA}$) : excitation
13	3	6	<i>IR2</i> ($\lambda = 8500\text{\AA}$) : excitation
14	4	6	<i>IR3</i> ($\lambda = 8544\text{\AA}$) : excitation
15	5	6	excitation
16	1	7	double ionization : ignored
17	2	7	2nd continuum : ionization from the fundatmental state of <i>CaII</i> to the fundamental state of <i>CaIII</i>
18	3	7	3rd continuum : ionization
19	4	7	4th continuum : ionization
20	5	7	5th continuum : ionization
21	6	7	6th continuum : ionization

Table 2: Main transitions for calcium

6.3 Magnesium

Four lines are considered : h (2803\AA), k (2796\AA), 2791\AA and 2798\AA .

In this case, we consider 6 levels (according to the atomic data of PANDORA, [2]) and 4 radiative transitions (see figure 7). In table 3, are described the considered transitions.

In PRODOP code, $NN = 6$ (4 Mg II levels, 1 Mg I level (fundamental), 1 Mg III level (fundamental)), $NTT = 15$ (total number of transitions), $NTC = 9$ (number of collisional transitions), $NTRC = 5$ (number of “continua” i.e. bound-free transitions), $NTRD = 4$ (number of lines).

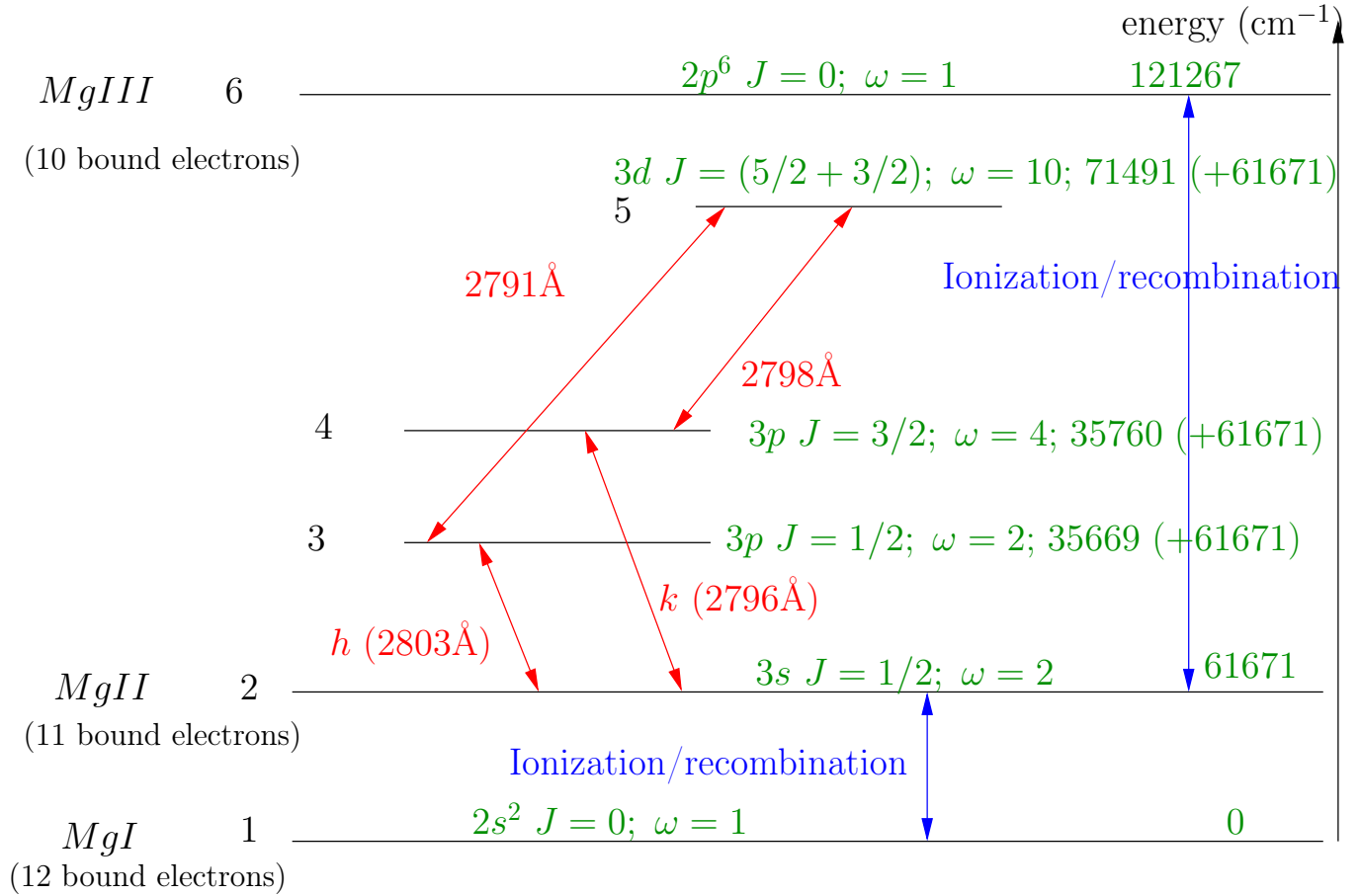


Figure 7: Description of magnesium levels (figure is not to scale) - 4 radiative transitions (in red). $\omega = 2J + 1$ is the statistical weight of the considered level

Transition NT	Lower level NI	Upper level NS	Transition name
1	1	2	1st continuum : ionization from the fundamental state of <i>MgI</i> to the fundamental state of <i>MgII</i>
2	1	3	ionization : ignored
3	2	3	<i>h</i> line ($\lambda = 2803\text{\AA}$) : excitation
4	1	4	ionization : ignored
5	2	4	<i>k</i> line ($\lambda = 2796\text{\AA}$) : excitation
6	3	4	excitation : ignored
7	1	5	ionization : ignored
8	2	5	excitation : ignored
9	3	5	(subordinate) line at 2791\AA : excitation
10	4	5	(subordinate) line at 2798\AA : excitation
11	1	6	double ionization : ignored
12	2	6	2nd continuum : ionization from the fundamental state of <i>MgII</i> to the fundamental state of <i>MgIII</i>
13	3	6	3rd continuum : ionization
14	4	6	4th continuum : ionization
15	5	6	5th continuum : ionization

Table 3: Main transitions for magnesium

For more details, see the description of MGIIP subroutine in the section 9.5.1.

6.4 Helium

In PRODOP code, we consider :

- $NN = NN1 + NN2 + 1 = 34$ energy levels (including the treshold level continuum) with $NN1 = 29$ and $NN2 = 4$
- $NTC = NTCE1 + NTCE2 + NN - 1$ collisional transitions with $NTCE1 = NN1 * (NN1 - 1)/2 - 7$ and $NTCE2 = NN2 * (NN2 - 1)/2$
- $NTRD = 76$ lines
- $NTRC = NN - 1$ “continua” i.e. bound-free transitions

For more details, see the thesis of N. Labrosse : “Modélisation du spectre de l’hélium dans les protubérances solaires” [18].

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:

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

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

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

where C_{ji} is the collisional deexcitation rate, proportional to the electron density. R_{ji} is the radiative depopulation "probability" (i.e. rate) either by absorption and by spontaneous (A_{ji}) or by stimulated emission. A_{ji} and B_{ji} are corresponding to Einstein coefficients (see figure 5).

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

$$P_{ij} = B_{ij} \bar{J}_{ij} + C_{ij} = R_{ij} + C_{ij},$$

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:

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

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:

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

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:

$$\sum_{j=1}^n N_j = N_T \quad (7.5)$$

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 by Feautrier's method:

$$\mu \frac{dI_\nu}{d\tau_\nu} = I_\nu - S_\nu \quad (7.6)$$

τ_ν is the optical depth at frequency ν , and S_ν is the 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 ([12]). For more details, see the next two sections.

8 Formalism used for radiative transfer

We start with an initialization: level populations, radiation field, electron density, atomic parameters (Einstein A and B coefficients, collision rate coefficients), model, incident intensities, boundary conditions. Then we enter in the iterative processes:

- The first external loop (*ITG*) concerns the computation of the statistical equilibrium, the calculation of the redistribution functions for the lines, the calculation of the variable Eddington factors, under the assumption of an optically thin medium (i.e. without radiative transfer).
- The second inner loop (*ICR*) concerns radiative transfer for continuum transitions and discrete transitions. It ends with a convergence test. Then we recalculate the new radiative parameters (P_{ji}) as well as the radiation temperatures for the continua.

This summary concerns only hydrogen atom. For calcium, helium and magnesium atoms, we solve the radiative transfer and the statistical equilibrium equations without computing again the electron density.

The statistical equilibrium (7.1, 7.5) consists in solving a linear system (using elimination method) whose terms are obtained from the population and depopulation coefficients P_{ji} (7.2). The unknown variables are level populations.

The radiative transfer (7.6) consists in calculating the intensities in the lines or in the continua starting from the knowledge of the source function and the intensities at the edge (boundary conditions). We use the so-called Feautrier method ([12, 22]), a method of solving a linear system resulting in a tridiagonal matrix. Each element of this tridiagonal matrix is a square matrix (direction-frequency). However, to reduce the size of the matrices, an integration on the direction is carried out using the variable Eddington factors (technique proposed by L. H. Auer and D. Mihalas, [1]). The original Feautrier method would have produced square matrices of size 60, whereas here matrices of size 20 are obtained, which

considerably reduces the computation time. As output, we obtain the intensities J_ν (7.4) averaged over all the directions from which we can recalculate new source functions and new transition rates. Source functions will be used later to calculate emergent intensities and line profiles.

For lines, two processes of frequency redistribution are used. Partial redistribution concerns only the photons absorbed and reemitted in the same line. The complete redistribution consists in supposing that there is no relation between the frequency of the absorbed photon and the frequency of the re-emitted photon. It's usually what we use for the Paschen, Balmer and Lyman lines formed from high energy levels. For hydrogen, the partial redistribution concerns only the lines $Ly \alpha$ and $Ly \beta$.

Whereas for continua, there is no problem of frequency redistribution.

The subroutines called in PRODOP codes will be detailed in the next section.

9 Subroutine descriptions

The PRODOP program starts with reading the first parameters of the model (input file "model.dat", detailed below). Then it deals with the abundance of metals relative to hydrogen (subroutine INIMET, detailed in the paragraph 9.2). Finally the program sets up the mesh of the plane-parallel slab representing the prominence or the filament. The half slab of thickness $1/2 e$ (see figure 3) is divided into $NXMOD = 46$ meshes. In the case of a prominence defined by the parameter $IVERT = 1$, we consider that the total number of meshes is $NZ = NXMOD = 46$ (half slab) because of the symmetry of the problem. In the case of a filament ($IVERT = 0$), we consider that $NZ = 2 NXMOD - 1 = 91$ (whole slab). The program ends with the main subroutine P5EXE.

Here is the scheme of the main subroutine P5EXE:

- definition of the mesh in space (XMOD) and in frequency (XFR)
 - definition of the general options of the code (convergence criterion, ...)
 - definition of permitted transitions (beyond level 5 for H)
 - *do imdl = 1, ndml* : loop on atmosphere models
 - I. Hydrogen
 - II. Calcium
 - III. Helium
 - IV. Magnesium
- enddo*

Input files for PRODOP:

- * *intinc_H.dat*: hydrogen (half-profile) incident intensities (1st column: wavelengths in Å, 2nd column: intensities in $\text{erg/cm}^2/\text{s}/\text{sr}/\text{Hz}$)

- ★ intica.dat: calcium (half-profile) incident intensities (Heinzel data, 1st column: frequencies in Hz, 2nd column: intensities in $\text{erg/cm}^2/\text{s/sr/Hz}$)
- ★ intinc_He.dat: helium (half-profile) incident intensities (1st column: frequencies in Hz, 2nd column: intensities in $\text{erg/cm}^2/\text{s/sr/Hz}$)
- ★ inting.dat: magnesium (half-profile) incident intensities (h and k lines: Heinzel data, [11]). The 1st column corresponds to the frequencies in Hz, the 2nd column to the intensities in $\text{erg/cm}^2/\text{s/sr/Hz}$
- ★ tembri.dat: brightness temperatures for solar flux, on the entire disk (1st column: wavelength in microns, 2nd column: temperature in K)
- ★ model.dat: file including the number of models to be computed and for each model, a line containing 6 parameters (temperature (K), pressure (dyn/cm^2), thickness (km), microturbulent velocity (km/s), altitude (km) from the sun's surface, bulk velocity (km/s)). The file starts with the following options:
 - IOEL: atomic elements to be treated (0:H, 1:H+He, 2:H+He+Ca+Mg, 3:H+Ca, 4:H+Mg)
 - IOPCAC: continuum absorption option (=3: with continuum absorption) (=0: without continuum absorption)
 - IOPEAC: writes continuum absorption coefficients (=1) or not (=0) in the output file fort.66
 - IVHYD: writes H lines list(=1) or not (=0) in the output file fort.66
 - IWRCCR: writes the radiative cooling rate (=1) or not (=0) in the output file fort.66
 - IVERT (1: prominence, 0: filament), IPCI (0: isothermal and isobaric model, 1: variable parameters across the solar structure)
 - NZMOD : number of layers (meshes) in the half slab
 - NMDL : number of atmosphere models

Output files for PRODOP:

- ★ resume.dat : iteration summary
- ★ fort.66 (list of transitions), fort.10 (resume.dat i.e. iteration summary), fort.21 (profilh.dat i.e. H profile in digital form), fort.51 (profihe.dat i.e. He profile in digital form), fort.81 (profica.dat i.e. Ca profile in digital form), fort.91 (profimg.dat i.e. Mg profile in digital form), fort.20 (fisuphy.dat i.e. hydrogen incident intensities)

After running the visualization program (see section 11), we obtain the following files in postscript format: profica.ps (Ca emergent profile), profihe.ps (He emergent profile), profilh.ps (H emergent profile), princ.ps (H incident profile), profimg.ps (Mg emergent profile), pinimg.ps (Mg incident profile), pinche.ps (He incident profile), pinca.ps (Ca incident profile).

In the next sections, hydrogen, calcium, helium and magnesium parts will be explained in details, as well as all subroutines called by PRODOP code and a set of variables used in the main subroutine P5EXE.

9.1 Description of major variables used in P5EXE subroutine

- IVERT = 0: filament model (horizontal slab), IVERT=1: prominence model (vertical slab)
- NMDL: number of atmosphere models to be computed
- NXMOD: number of meshes (or subdivisions) in the half slab
- NZ: total number of meshes
- 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 and MGIIIP subroutines: for the computation of collisional ionization and excitation (rate) coefficients OIS)
- NINF: transition lower level
- NSUP: transition upper level
- ITP: indicates if the transition is permitted 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* α)
- 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 $\mu = \cos \theta$ (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). θ is the angle between the light ray and the normal to the solar surface
- 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 rates
- 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 of size NZ) : XM (column-mass), Z (position in the slab), TE (temperature), PG (gas pressure), VTKMS (microturbulent velocity), VKMS (bulk 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
- RXRO: relaxation parameter to ensure convergence
- CRITR: convergence criterion
- HN: level population of hydrogen in cm^{-3} (the number of atoms in the considered state in cm^3)

9.2 Hydrogen (Johnson model, [13])

Hydrogen modeling is divided into 4 parts:

1. Initialization of atmosphere parameters:

- Reading atmospheric parameters (model.dat)
- INIFEV : initialization of Eddington's factors for permitted transitions (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 (rate) coefficients)
- SOLINH (subroutine called once for imdl=1): incident intensities (input file "intinc_H.dat") and brightness temperatures (input file "tembri.dat") are read. Line intensities non defined in "intinc_H.dat" are computed from "tembri.dat"
- INTALT : computation of dilution factors (lines and continua) taking into account the limb darkening and the altitude of the prominence/filament ($FADIR$: dilution factors for lines, $FADIC$: dilution factors for continua)
- COLIDH : boundary conditions for H (intensities) for a moving vertical plane-parallel slab
- Computation of the integral over the line profile $HJBAR = \int_{-\infty}^{+\infty} J_\nu \Phi_\nu d\nu$
- WRITFIS : writes boundary conditions (i.e. incident intensities) DLA and FTLA on output files for each atomic element (H, He, Mg, Ca)
- INITR1 : initialization of radiation temperatures for hydrogen (corresponding to the radiation of a black body) for bound-free transitions from dilution factors and incident radiation temperatures

2. General loop for hydrogen:

do $ITG = 1, ITGMAX$:

- HYESV3: solves statistical equilibrium and ionization (computation of H level populations and electron density)
- ABSCON (if IOPCAC=3): computation of the continuum absorption in the neighbourhood of the studied lines
- 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” (i.e. rates) *RIK* and *RKI*) and for *HN* (H level populations)
- *do icr = 1, ICRMAX*: loop (internal) on the pressure equilibrium
Hydrogen ionization determines free electron density.
 - EQSTHV3: solves 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 continua and lines)
 - Bound-Free transitions:
 - ★ *do itac = 1, NTAC*: loop on continua
 - HCONTI: Non-LTE radiative transfer for continua. Intensities and transition probabilities P_{ji} defined by (7.2) are computed
 - ★ *enddo* (for *itac*)
 - ★ COMPACH: comparison for convergence (continua)
 - Bound-Bound transitions:
 - ★ *do itar = 1, NTAR*: loop on lines
 - RPRHV3: Non-LTE radiative transfer for lines
 - ★ *enddo* (for *itar*)
 - ★ COMPARH: comparison for convergence (lines)
 - ★ Preparation of the next iteration (definition of ECMX): 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* for lines and *FKTC* for 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
 - ABSCON: continuum absorption due to different elements is computed (defined in INIMET subroutine)
 - EQSTHV3

- ECRIPOP: writes H level populations in output file fort.66
- For lines
 - RPCDEH
 - RPRHV3
 - SUMRA (if IOPRA=1): writes wavelengths *AMBDA*, etc
 - PROFLI: line profiles
- For continua
 - HCONTI
- COMPARH
- COMPACH
- RADCOV3 (if IWRCR=1)
- If ICV = 0 then (if the 1st atmosphere model has been treated)
 - ★ NMDLC = NMDLC+1 (incrementation on models)
 - ★ definition of FR and BJ for levels (I=1,NN-1)
 - ★ POP31: writes H level populations (*HN*)
 - ★ RESUME_H: write the different quantities (total energy *ETOT*, wavelengths *AMBDA*, etc)
 - ★ SFTEST
 - ★ If IOEL=1 or 2 (Helium part): HTOHE (transition from hydrogen to helium) and FHELs (Non-LTE radiative transfer for helium)
 - ★ If IOEL=2 or 3 (Calcium part): HYTOCA (transition from hydrogen to calcium) and CAIIP (Non-LTE radiative transfer for calcium)
 - ★ If IOEL=2 or 4 (Magnesium part): HYTOMG (transition from hydrogen to magnesium) and MGIIP (Non-LTE radiative transfer for magnesium)
- endif (ICV=0)

We will now describe the subroutines called above.

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

INIFEV

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), *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 PRODOP 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 ([13]).

AJI is obtained by AEMS function (in PRODOP code) which is calculated from “Gaunt factors” (Table 1 in [13]).

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 PRODOP code):

Let *n* and *n'* be two levels ($n < n'$). The excitation (rate) coefficient is given by the following formula (Johnson, [13]), implemented in PRODOP code:

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

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

m denotes the electron mass and $a_0 = 0.5292 \cdot 10^{-8}$ cm the Bohr radius.

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

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

where g_0 , g_1 , g_2 : Gaunt factors for pour Bound-Free transitions. They are given in Table 2 (Table 1 in [13]) :

	$n = 1$	$n = 2$	$n \geq 3$
$g_0(n)$	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 4: Gaunt factors

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

Let us consider here level n . The ionization (rate) coefficient is given by the following formula (Johnson, [13]) implemented in PRODOP code:

$$\begin{aligned}
S_i(n) &= (8kT/\pi m)^{1/2} 2n^2 \pi a_0^2 y_n^2 A_n \left[\frac{1}{y_n} E_1(y) - \frac{1}{z_n} E_1(z_n) \right] \\
&\quad + (8kT/\pi m)^{1/2} 2n^2 \pi a_0^2 y_n^2 (B_n - A_n \ln 2n^2) [\zeta(y_n) - \zeta(z_n)],
\end{aligned} \tag{9.2}$$

where m is the electron mass and

$$\begin{aligned}
y_n &= I_n/kT, \\
z_n &= r_n + I_n/kT, \\
\zeta(t) &= E_0(t) - 2E_1(t) + E_2(t)
\end{aligned}$$

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_H.dat” contains incident intensities for $NLI = 17$ hydrogen lines (1st column: wavelengths in Å, 2nd column : intensities in $\text{erg/cm}^2/\text{s}/\text{sr}/\text{Hz}$). 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_H.dat”.

Inputs: NN , NTT , $NTAR$, $NFIMX$, $NCMX$, $NINF$, $NSUP$, NFR , NTR , $ICTR$, $NFINT$

Output: $FINT$

INTALT

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

Inputs: $ALTI$, $NTAR$, $NTAC$, $NCMX$, $CPOL$

Outputs: $FADIR$ (for lines) and $FADIC$ (for continua).

COLIDH

Boundary conditions (CL) for H (intensities) for a moving vertical plane-parallel slab (for lines and continua)

Inputs: $VKMS$, HKM , $NCMX$, $CPOL$, NZ , NN , NTT , $NTRD$, $NTRC$, NFR , $NFRC$, $NFIMX$, $ITRD$, $ICTR$, $NINF$, $NSUP$, FRN , DN

Outputs: lower and upper boundary conditions for continua (FIIC, FISC) and for lines (FIIR, FISR), GIOM

WRITFIS

Writes boundary conditions in the output file “fort.LU” where LU is an integer.

Outputs: *FILA*, *DLA*

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 ([4]). 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” (i.e. rates : CIJ et CJI) are computed by using electron density.

INIRIKH: photoionization “probabilities” (i.e. rates) 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 continuum absorption 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), continuum source functions FSC , coherent scattering ratios $CSCAT$ for a given frequency $FREQ$, and continuum 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 ([4])), carbon, magnesium, silicon 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

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

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

MRDBIL: 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 , $PHIX$

Output 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 used for statistical equilibrium).

HCONTI uses the following subroutines:

CSIETAH: 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 functions S . We use Feautrier method and variable Eddington factors

NOVFEV: computes new Eddington factors (outputs: *FEVK* and *FEVL*) from source functions ([1]). 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)

RPRHV3

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 the source function *SR* in the line and the total source function *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: *BRN*

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 $\mu = \cos \theta$.

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)

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

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)
- **RESUME_H**: 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 measure $EMEU$
- **CAIP**: 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 $GINU = J_\nu = \frac{1}{4\pi} \oint I_\nu d\omega$ (ω is the solid angle) from source function 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: $CABF$ and $CEBF$ (absorption and emission coefficients for continua), $CADP$ (coefficients for pure diffusion)

CAIIP : Processing for Ca II lines

In PRODOP code, $NN = 7$ (5 Ca II levels, 1 Ca I (fundamental) level, 1 Ca III level (fundamental)), $NTT = 21$ (total number of transitions), $NTC = 16$ (number of collisional transitions), $NTRC = 6$ (number of bound-free transitions), $NTRD = 5$ (number of lines).

Here are some definitions of variables used in CAIIP subroutine (see figure 6 and table 2) :

- NUMAT: calcium atomic number
- HMA: calcium atomic mass
- ABOND: abundance of Ca relative to H
- INF: array (of size NN) which contains 1 (if it is a fundamental level) and 0 (if it is an intermediary level). INF=/1,1,0,0,0,0,1/
- POM: array of size NN containing the statistical weights of each calcium level. POM=/1,2,4,6,2,4,1/
- FRN: array of size NN representing the frequency of levels. CL is the speed of light in cm/s.
 - ★ FRN(1) = 0
 - ★ FRN(2) = 49306×CL where 49306 is the ionization energy of Ca I
 - ★ FRN(3) = FRN(2)+13650.21×CL
 - ★ ...
for more details, see figure 6
- ITC: array of size NTC corresponding to the transition number for which collision rate coefficients are computed (see table 2). ITC=/1,3,5,6,8,9,10,12,13,14,15,17,18,19,20,21/
- TAB: array of size NTAB containing electron temperatures which are used as reference temperatures to array OIS
- OIS: array of size (NTAB,NTC) containing the ionization and collisional excitation coefficients for each transition and for each TAB temperature
- ITRD: array of size NTRD corresponding to the number of lines (see table 2). ITRD=/8,9,12,13,14/
- ICTR: array of size NTRD, filled of 1 (if it is a permitted transition). ICTR=/1,1,1,1,1/
- AJI: array of size NTRD corresponding to spontaneous emission probabilities (data from NIST)
- IOPRN: array of size NTRD, filled with 1 (if we treat the line in CRD) and with 3 (if we treat the line in PRD, it is the case of resonance lines)

- **FADI**: array of size **NTRD** corresponding to dilution factors
- **ITRC**: array of size **NTRC** corresponding to bound-free transition number. **ITRC**=/1,17,18,19,20,21/
- **OREF**: array of size (**NFRC,NTRC**) corresponding to the wavelengths (\AA) for each continuum transition
- **ALP**: array of size (**NFRC,NTRC**) containing photoionization cross sections for continuum

CAIIP uses the following subroutines:

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

INIFEVCA: initialization of variable Eddington factors

INITESCA: 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*.

INIRIK2: computation of radiative transition probabilities for calcium continua (bound-free transitions) from *GINU* obtained by **HYTOCA** subroutine. Outputs: *RIK*, *RKI*

TXCOLL: see hydrogen modeling

COLIDCA: boundary conditions for a moving vertical parallel plane slab. **VDOP** is the Doppler velocity (dimensionless number). **GAM** represents the directions. **FRDOP** is the Doppler frequency

WRITFIS: writes boundary conditions in an output file “fort.LU”, where **LU** is an integer

RPCDCA: equivalent to **RPCDEH** subroutine for hydrogen.

RPCDCA computes redistribution matrix and uses *ELCOCA* (computation of collisional broadening for Ca II lines) and *MRDBIL* (see hydrogen modeling) subroutines

EQSTGV3: equivalent to **EQSTHV3** subroutine for hydrogen. Statistical equilibrium equation for calcium excited level populations are solved. Output: *HN*

RPRGV3: equivalent to **RPRHV3** subroutine for hydrogen. Non-LTE radiative transfer is computed for calcium lines

COMPAR: equivalent to **COMPARH** subroutine for hydrogen.

NOVBRV3: see hydrogen modeling

SUMRA: writes the following quantities **TO**, **BEN**, **GIBAR**, **COHE**, **EPS** in the output file “fort.66”

PROFCAL: computation of emergent profiles of Ca II lines

POP31: see hydrogen modeling

SFTEST: see hydrogen modeling

ELCOCA: computation of collisional broadening for Ca II lines

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, PROFLL, PROEM2, POP31, SFTEST.

9.4 Helium

The helium modeling is divided into 2 parts:

HYTOHE: transition from H to He

FHEL: Non-LTE radiative transfer for helium.

For more details, see N. Labrosse’s thesis: “Modélisation du spectre de l’hélium dans les protubérances solaires” ([18]).

9.5 Magnesium

The magnesium modeling (Non-LTE radiative transfer for 4 Mg II lines: h (2803 Å), k (2796 Å), 2791 Å and 2798 Å) is divided into 2 parts:

HYTOMG: transition from hydrogen to magnesium. Absorption and emission coefficients linked to continua and pure diffusion are computed (same process for calcium, see HYTOCA subroutine). We consider for hydrogen the populations of the first 5 levels as well as the continuum.

MGIIP: this subroutine is divided into two parts. The first part concerns atomic parameters, described in paragraph 9.5.1. The second part concerns the non-LTE radiative transfer for Mg II lines, described in paragraph 9.5.2.

The **input** file containing the incident intensities (**half-profile**) of the 4 magnesium lines is “inting.dat” (h and k lines: Heintzel data, [11]). It is described as follows:

- 1st line: number of the line, number of points
- the other lines: frequency in Hz (1st column), intensity in $\text{erg}/\text{cm}^2/\text{s}/\text{sr}/\text{Hz}$ (2nd column)

This process is applied for the 4 magnesium lines in the following order:

- line n°1 : h line
- line n°2 : k line
- line n°3 : 2791 Å
- line n°4 : 2798 Å

9.5.1 Atomic data

$NN = 6$ levels, $NTC = 9$ collisional transitions, $NTRD = 4$ lines, $NTRC = 5$ bound-free transitions, $NTAB = 3$ (size of the TAB array of temperature corresponding to the transi-

tion coefficients (see OIS below) from the PANDORA data, see appendix 14) are considered. Here are the description of major variables used in MGIIP subroutine. Refer to the figure 7 and the table 3 for the values of the arrays defined below and above.

- NUMAT=12: magnesium atomic number
- HMA=24.305: magnesium atomic mass
- ABOND= 3.388×10^{-5} : abundance of Mg relative to H (PANDORA data: [2], appendix 14)
- INF: array of size NN, which contains 1 (if it is a fundamental level) and 0 (if it is an intermediary level). INF=/1,1,0,0,0,1/
- POM: array of size NN corresponding to the statistical weights of each level (according to PANDORA data and the description of magnesium levels in the figure 7). POM=/1,2,2,4,10,1/
- FRN: array of size NN corresponding to the frequency of the levels. CL is the speed of light in cm/s.
 - ★ FRN(1) = 0
 - ★ FRN(2) = 61671×CL where 61671 is the ionization energy of Mg II
 - ★ FRN(3) = FRN(2)+35669.31×CL
 - ★ ...
 for more details, see figure 7
- ITC: array of size NTC corresponding to the transition number for which collision rate coefficients are computed (see table 3). ITC=/1,3,5,9,10,12,13,14,15/
- TAB: array of size NTAB corresponding to electron temperatures which are used as reference temperatures to array OIS (see below). TAB=/ 4.E3, 8.E3, 16.E3 /
- OIS: array of size (NTAB,NTC) corresponding to ionization (rate) coefficients (CI of appendix 14 on PANDORA data) and to collisional excitation (rate) coefficients (CE of appendix 14 on PANDORA data) for each transition and temperature TAB. Refer to table 3 and appendix 14.

(OIS(J,1),J=1,3)=/ 6.4E-8, 9.5E-8, 1.43E-7 / : *CI data of Mg I table, Pandora*

(OIS(J,2),J=1,3)=/ 3.578E-7, 2.663E-7, 2.048E-7 / : *CE data for h line of Mg II table, Pandora*

(OIS(J,3),J=1,3)=/ 7.152E-7, 5.327E-7, 4.097E-7 / : *CE data for k line of Mg II table, Pandora*

(OIS(J,4),J=1,3)=/ 1.028E-6, 7.632E-7, 5.805E-7 / : CE data for 2791 Å line of Mg II table, Pandora
(OIS(J,5),J=1,3)=/ 8.246E-7, 6.088E-7, 4.54E-7 / : CE data for 2798 Å line of Mg II table, Pandora
(OIS(J,6),J=1,3)=/ 1.328E-8, 1.138E-8, 1.245E-8 / : CI data for the 2nd continuum of Mg II table, Pandora
(OIS(J,7),J=1,3)=/ 2.321E-8, 3.103E-8, 3.989E-8 / : CI data for the 3rd continuum of Mg II table, Pandora
(OIS(J,8),J=1,3)=/ 2.326E-8, 3.109E-8, 3.997E-8 / : CI data for the 4th continuum of Mg II table, Pandora
(OIS(J,9),J=1,3)=/ 7.868E-8, 1.017E-7, 1.247E-7 / : CI data for the 5th continuum of Mg II table, Pandora

- ITRD: array of size NTRD corresponding to the number of lines (see table 3). ITRD=/3,5,9,10/
- ICTR: array of size NTRD, filled of 1 (if it is a permitted transition). ICTR=/1,1,1,1/
- AJI: array of size NTRD corresponding to spontaneous emission probabilities (data from NIST)
- IOPRN: array of size NTRD, filled of 1 (if we treat the line in CRD) and with 3 (if we treat the line in PRD, it is the case of resonance lines)
- FADI: array of size NTRD corresponding to dilution factors
- ALP: array of size (NFRC,NTRC) corresponding to the photoionization cross sections
- OREF: array of size (NFRC,NTRC) corresponding to the wavelengths (Å) for each continuum transition
- ITRC: array of size NTRC corresponding to bound-free transition number. ITRC=/1,12,13,14,15/

The values of the OIS, POM tables come from the PANDORA data (appendix, [2]).

If ICVAL = 1, we consider TAB and OIS arrays. If ICVAL = 0, we consider SIGM array (of size NTC) which is the ionization cross section by collision, instead of TAB and OIS.

9.5.2 Non-LTE radiative transfer for the four Mg II lines

The second part of the MGIIIP subroutine concerns the formation of magnesium lines in solar structures (is identical to hydrogen, calcium and helium). It uses the following subroutines:

- **SOLIMG:** reads incident intensities of magnesium (“intimg.dat” file).

- **INIFEVCA:** initialization of Eddington factors
- **INITESCA:** classification of transitions for magnesium
- **TXCOLL:** see hydrogen modeling
- **COLIDMG:** boundary conditions for a moving vertical parallel plane slab. VDOP is the Doppler velocity (dimensionless number). GAM represents the directions directions. FRDOP is the Doppler frequency. In this subroutine we symmetrize the half-profile “intimg.dat” of Mg incident intensities
- **WRITFIS:** writes boundary conditions in an output file “fort.LU”, where LU is an integer
- **RPCDMG:** equivalent to **RPCDEH** subroutine for hydrogen. RPCDMG computes redistribution matrix and uses *ELCOMG* (computation of collisional broadening for Mg II lines) and *MRDBIL* (see hydrogen modeling) subroutines
- **EQSTGV3:** equivalent to **EQSTHV3** subroutine for hydrogen. Statistical equilibrium equations for Mg excited level populations are solved by iterations. Output: HN
- **RPRGV3:** equivalent to **RPRHV3** subroutine for hydrogen. Non-LTE radiative transfer is computed for magnesium lines
- **COMPAR:** equivalent to **COMPARH** subroutine for hydrogen
- **NOVBRV3:** see hydrogen modeling
- **SUMRA:** writes in the output file “fort.66” the following quantities TO, BEN, GIBAR, COHE, EPS
- **PROFMG:** computation of emergent profiles of Mg II lines
- **POP31_Mg:** see hydrogen modeling
- **SFTEST:** see hydrogen modeling
- **ELCOMG:** computation of collisional broadening for Mg II lines

10 Results

In sections 10.1, 10.2, 10.3 and 10.4, we will give the emergent profiles for hydrogen lines, for *CaII*, for *HeI*, *HeII* and for *MgII* lines, obtained by the PRODOP program corresponding to a model of isothermal and isobaric atmosphere given (prominence case).

Emergent profiles are given for $\mu = \cos \theta = 1$.

10.1 Hydrogen

Figure 8 represents the ratio of integrated intensities ($E(V)/E(V=0)$) as a function of velocity (km/s) for $L\alpha$, $L\beta$ and $H\alpha$ lines. We consider the following model, with continuum absorption:

$T = 6500$ K, $p = 0.1$ dyn cm^{-2} , thickness = 650 km, $VT = 5$ km/s,
altitude = 10000 km.

The emergent profiles of the hydrogen lines for $V = 0$ km/s and $V = 100$ km/s are plotted in figures 9 and 10.

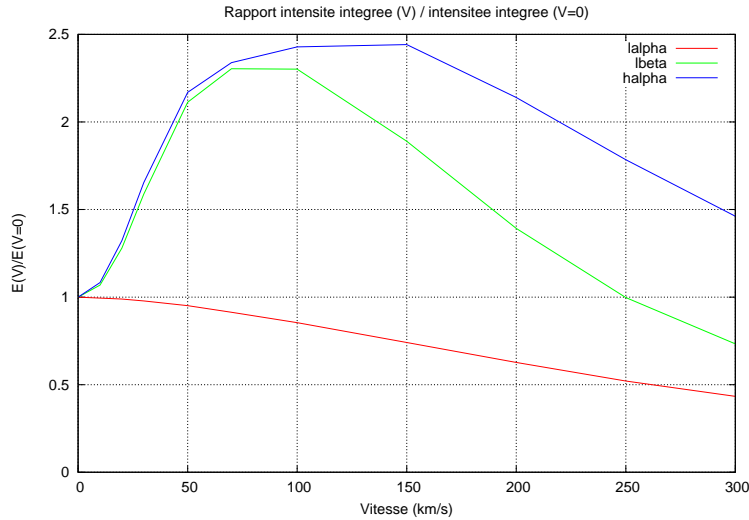


Figure 8: Ratio of integrated intensities ($E(V)/E(V=0)$) as a function of velocity for $L\alpha$, $L\beta$ and $H\alpha$ hydrogen lines

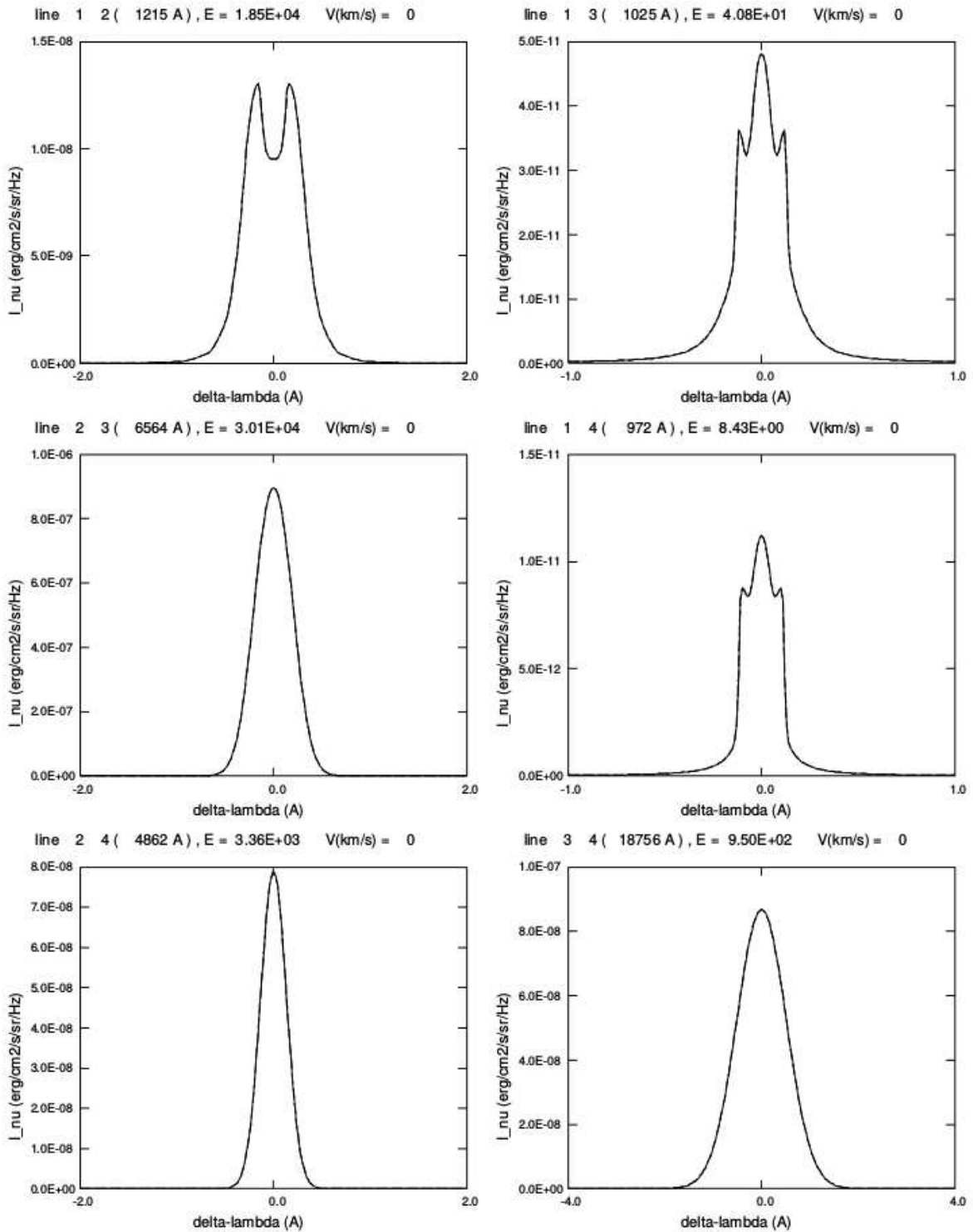


Figure 9: Line profiles (from left to right, from top to bottom) for $L\alpha$, $L\beta$, $H\alpha$, $L\gamma$, $H\beta$, $P\alpha$ hydrogen lines, for $V = 0$ km/s, with continuum absorption, for $\mu = \cos \theta = 1$. Abscissa (\AA), ordinate ($\text{erg/cm}^2/\text{s/sr/Hz}$)

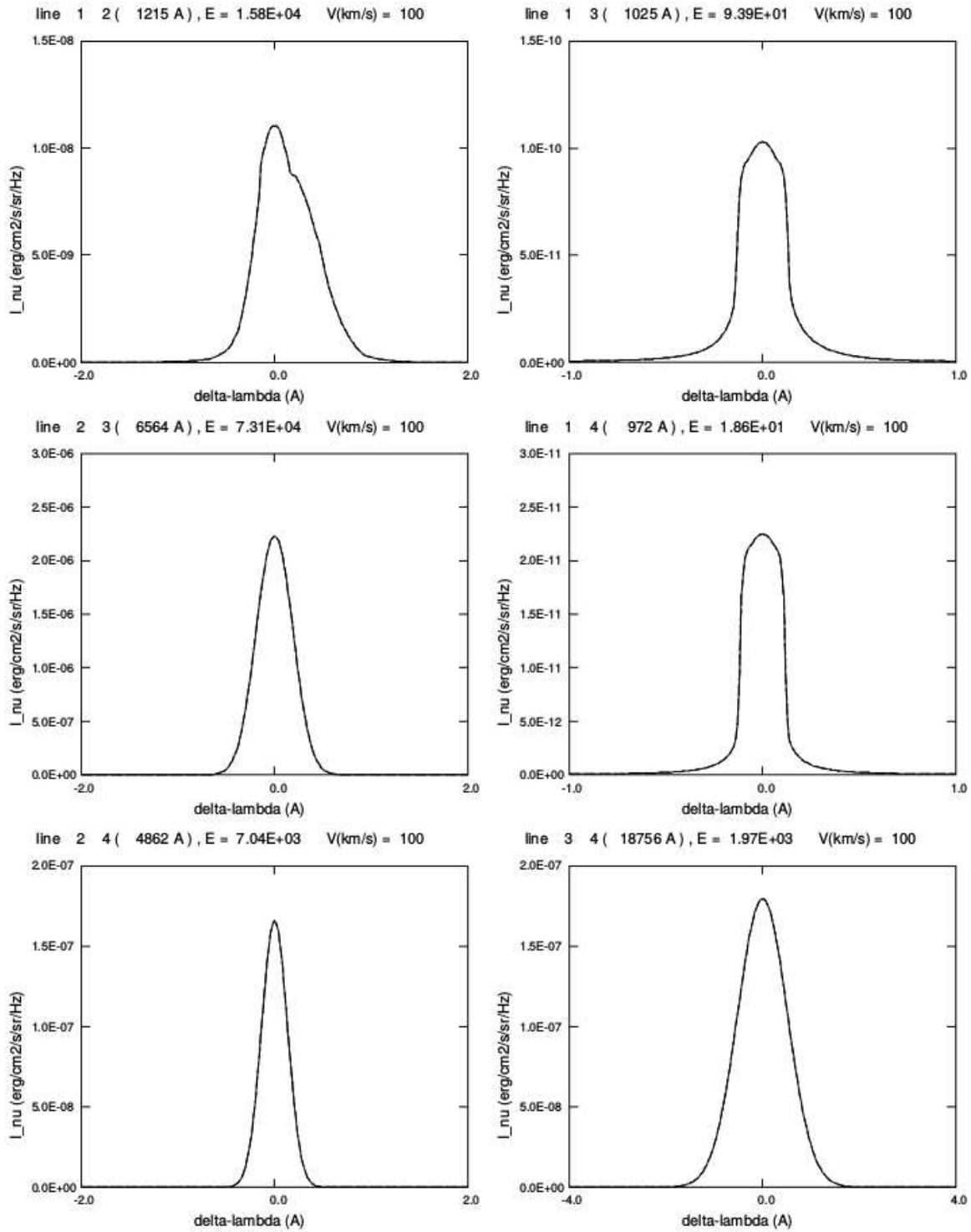


Figure 10: Line profiles (from left to right, from top to bottom) for $L\alpha$, $L\beta$, $H\alpha$, $L\gamma$, $H\beta$, $P\alpha$ hydrogen lines, for $V = 100$ km/s, with continuum absorption, for $\mu = \cos\theta = 1$. Abscissa (Å), ordinate (erg/cm²/s/sr/Hz)

10.2 Calcium

Figures 12 and 13 represent emergent profiles for Ca II lines, for $V = 0$ km/s and $V = 120$ km/s. The model considered is the following, including continuum absorption:

$T = 8000$ K, $p = 0.1$ dyn cm $^{-2}$, thickness = 1000 km, $VT = 5$ km/s, altitude = 10000 km.

Figure 11 represents the ratio of the integrated intensities ($E(V)/E(V=0)$) as a function of velocity.

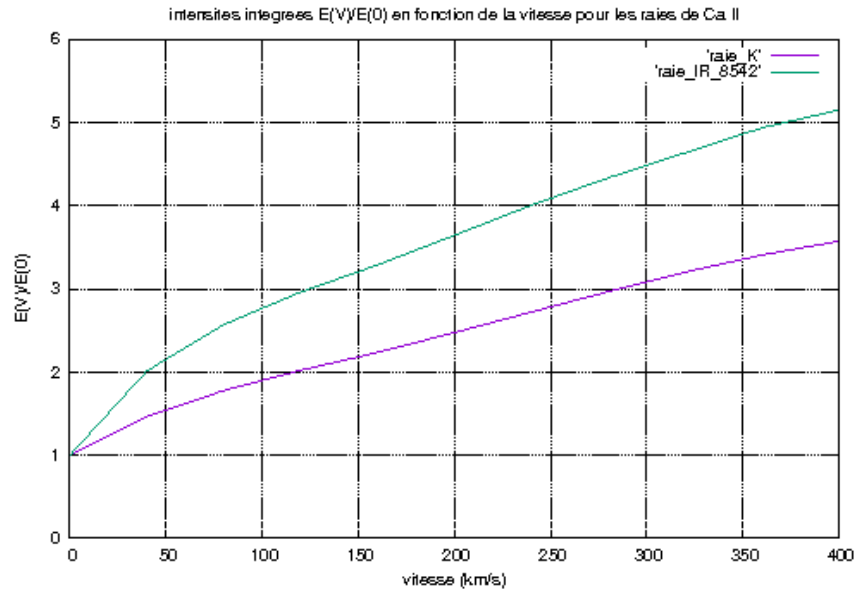


Figure 11: Ratio of the integrated intensities ($E(V)/E(V=0)$) as a function of velocity for K and IR3 Ca II lines, obtained by PRODOP code.

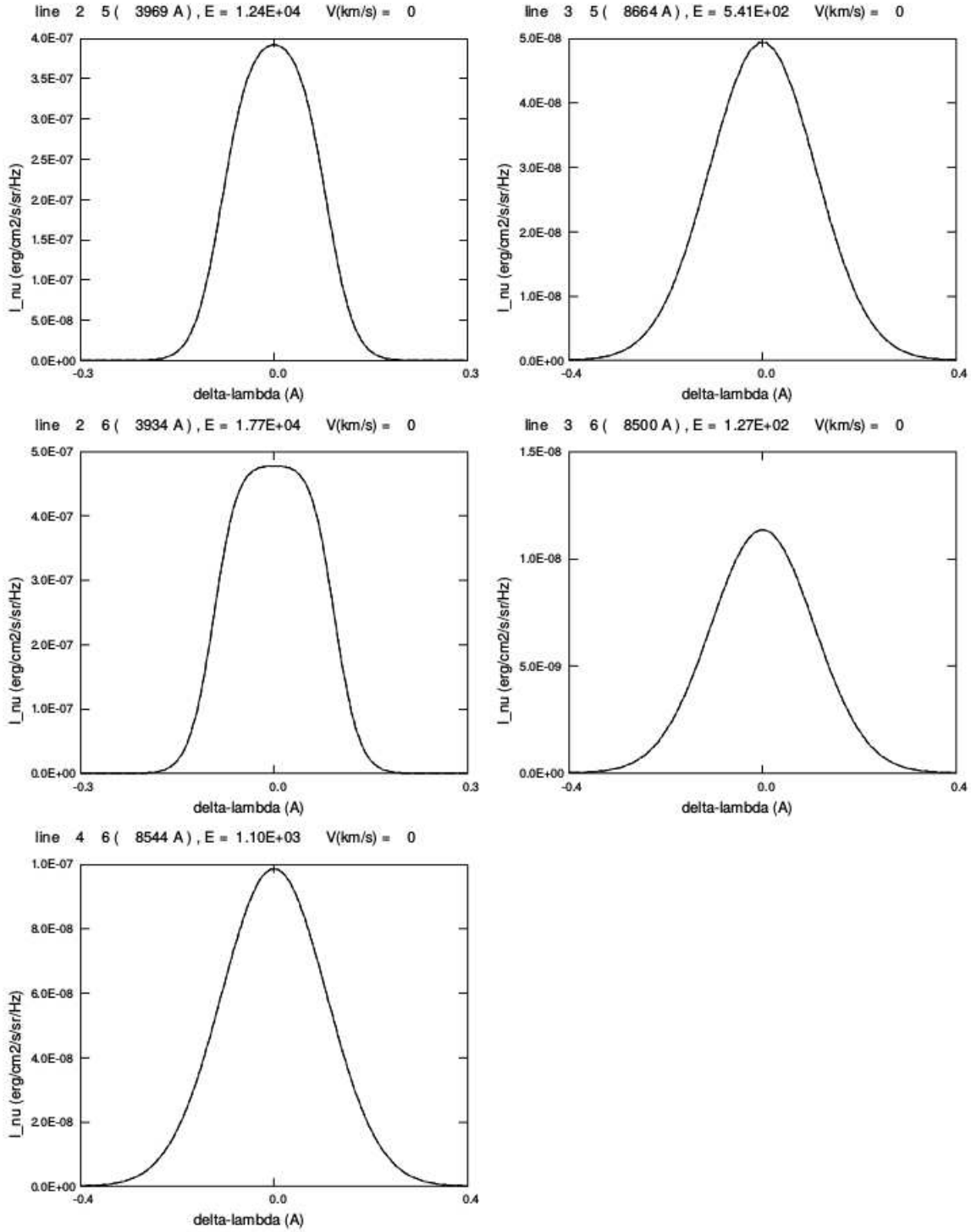


Figure 12: Line profiles (from left to right, from top to bottom) for H, IR1, K, IR2, IR3 Ca II lines, for $V = 0$ km/s, with continuum absorption, for $\mu = \cos\theta = 1$, obtained by PRODOP code. Abscissa (\AA), ordinate ($\text{erg/cm}^2/\text{s/sr/Hz}$)

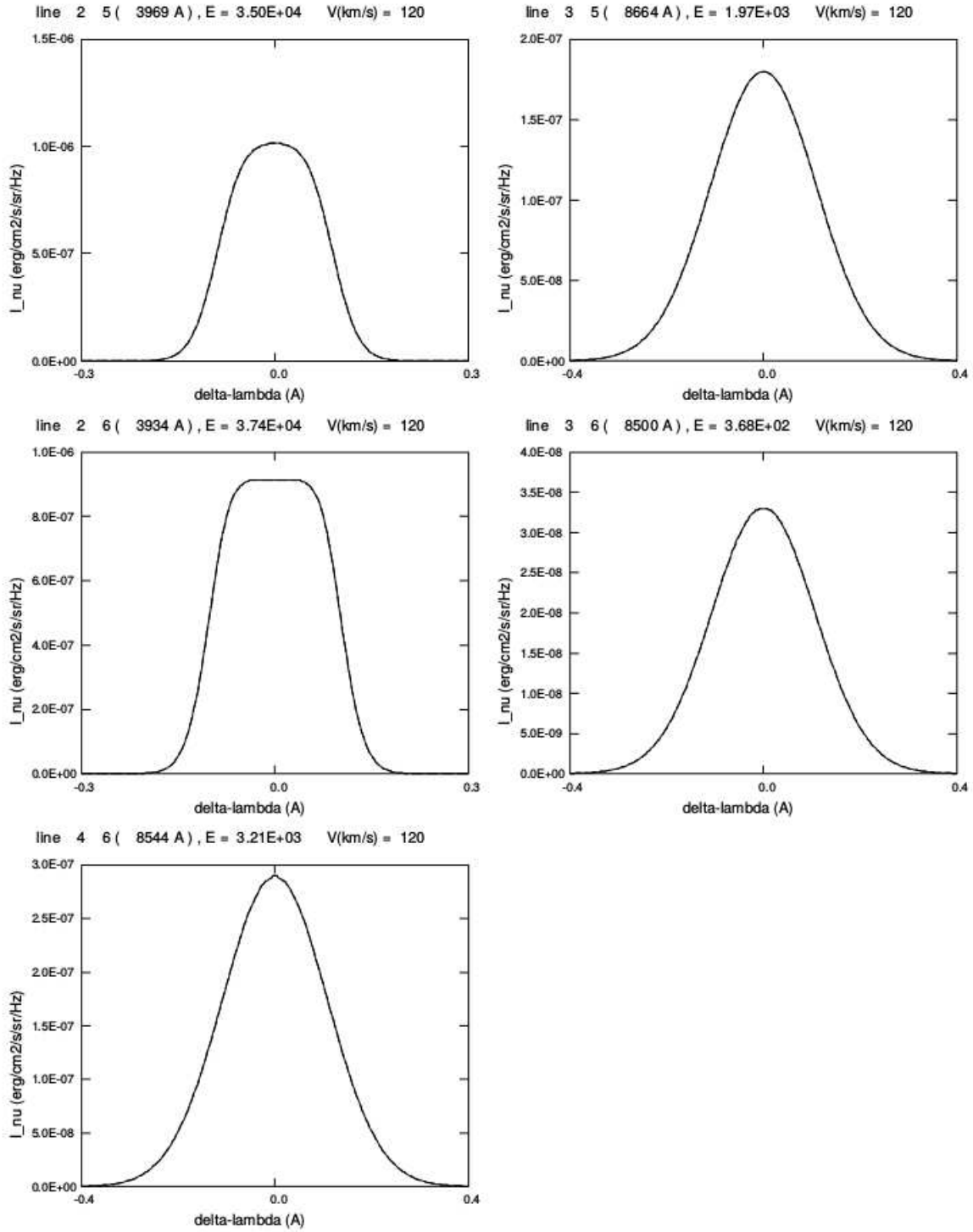


Figure 13: Line profiles (from left to right, from top to bottom) for H, IR1, K, IR2, IR3 Ca II lines, for $V = 120$ km/s, with continuum absorption, for $\mu = \cos \theta = 1$, obtained by PRODOP code. Abscissa (Å), ordinate (erg/cm²/s/sr/Hz)

10.3 Helium

Figures 14 and 15 represent line profiles for He I and He II lines, for $V = 0$ km/s and $V = 120$ km/s. There is no continuum absorption and the model considered is Labrosse's model ([15], [17]) :

$T = 8000$ K, $p = 0.1$ dyn cm⁻², thickness = 2000 km, $V_T = 0$ km/s, altitude = 50000 km.

Emergent profiles were plotted for 3 values of μ :

- $\mu = 1$: curve in plain line
- $\mu = 0.6$: curve in dashed line
- $\mu = 0.2$: curve in dotted line

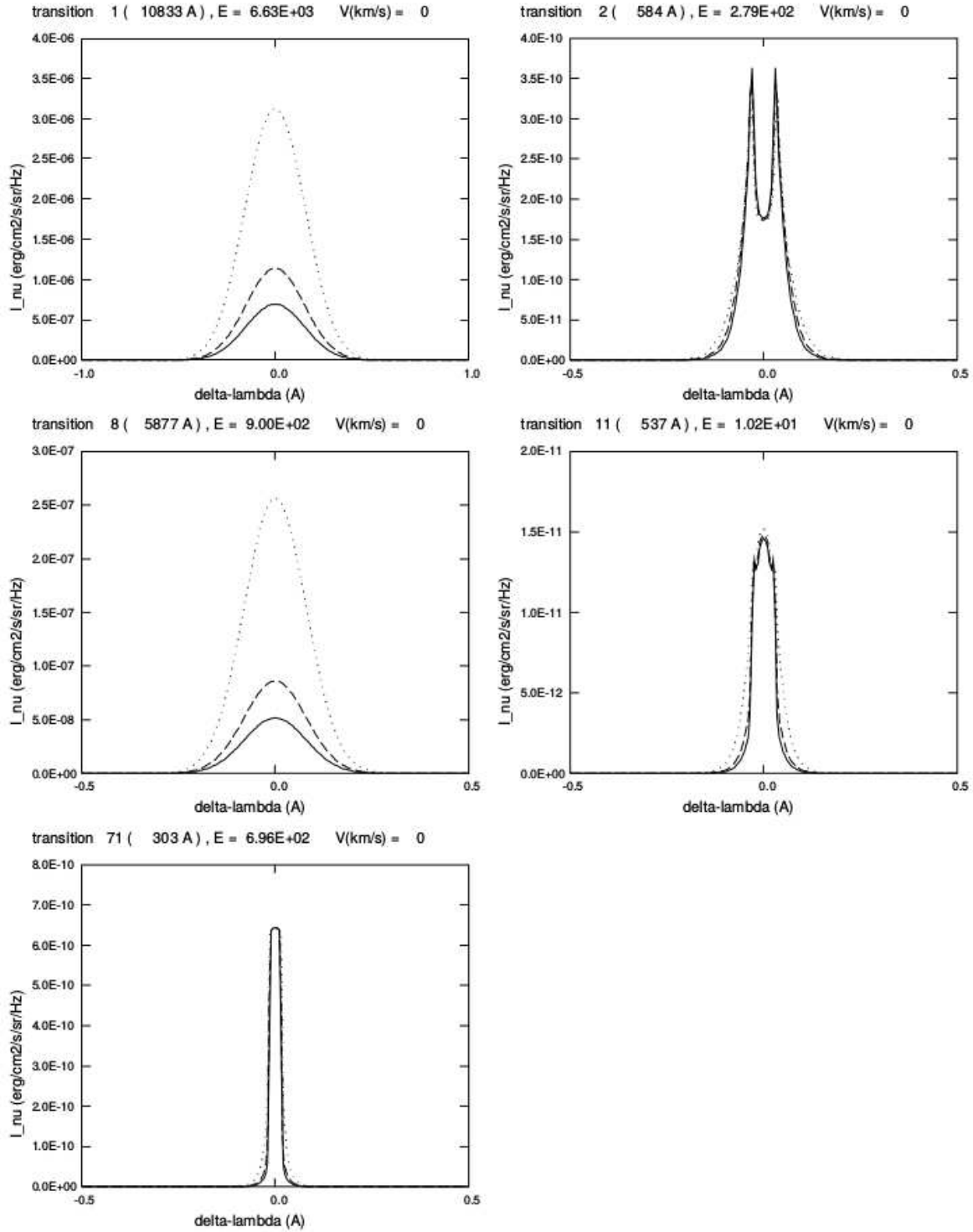


Figure 14: Line profiles (from left to right, from top to bottom) for HeI(10833 \AA), HeI(584 \AA), HeI(5877 \AA), HeI(537 \AA), HeII(303 \AA) lines, for $V = 0 \text{ km/s}$, without continuum absorption, for 3 values of $\mu = \cos\theta$ (1; 0.2; 0.6). Abscissa (\AA), ordinate ($\text{erg/cm}^2/\text{s}/\text{sr}/\text{Hz}$)

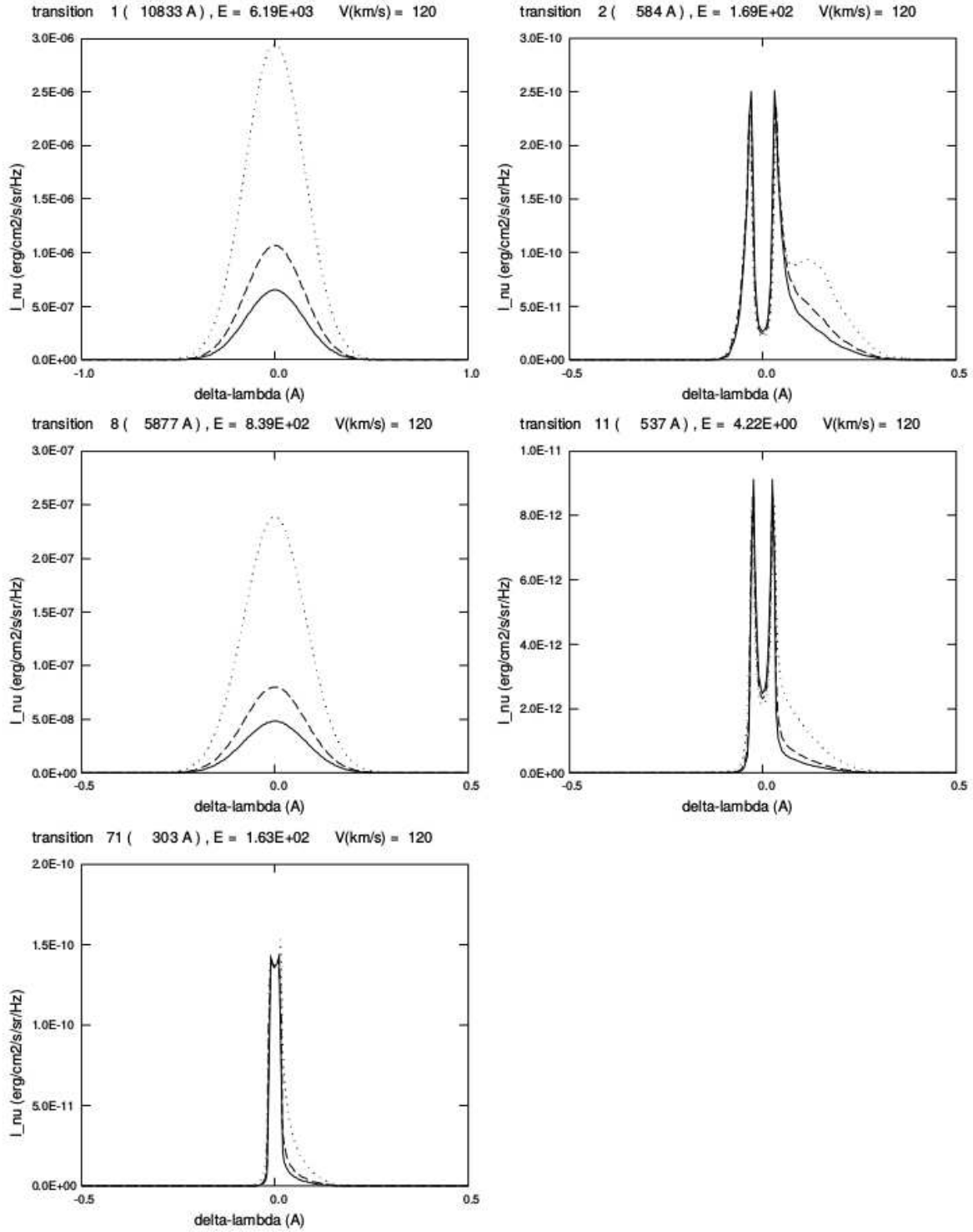


Figure 15: Line profiles (from left to right, from top to bottom) for HeI(10833Å), HeI(584Å), HeI(5877Å), HeI(537Å), HeII(303Å) lines, for $V = 120$ km/s, without continuum absorption, for 3 values of μ (1; 0.2; 0.6). Abscissa (Å), ordinate (erg/cm²/s/sr/Hz)

10.4 Magnesium

Incident intensities (Heinzel, [11]) for h and k lines are represented in figures 16 and 17.

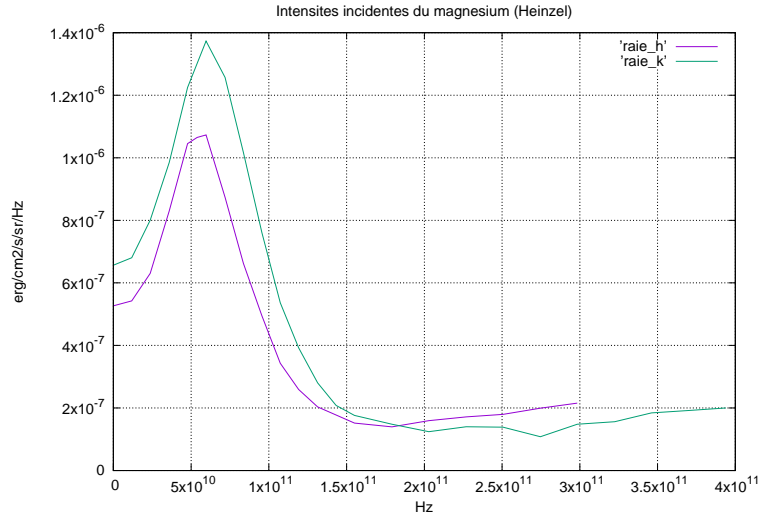


Figure 16: Incident intensities for h (2803 Å) and k (2796 Å) Mg II lines. Abscissa (Hz), ordinate ($\text{erg}/\text{cm}^2/\text{s}/\text{sr}/\text{Hz}$)

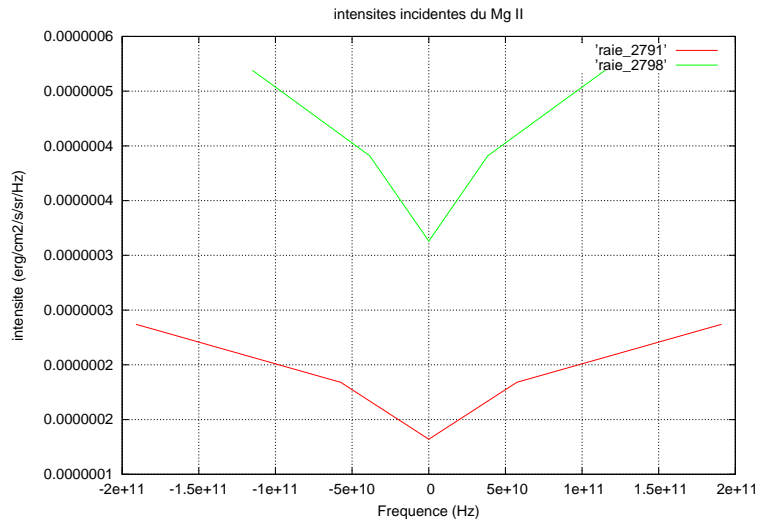


Figure 17: Incident intensities for Mg II subordinate lines (2791 Å and 2798 Å). Abscissa (Hz), ordinate ($\text{erg}/\text{cm}^2/\text{s}/\text{sr}/\text{Hz}$)

The results for h, k lines as well as for the two subordinate lines (2791 Å and 2798 Å) are represented in figures 18 and 19. The model considered is:

$T = 8000$ K, $p = 0.1$ dyn cm⁻², thickness = 1000 km, $V_T = 5$ km/s, altitude = 10000 km.

One takes here $V = 0$ km/s and $V = 120$ km/s. $\mu = \cos \theta = 1$. There is no continuum absorption.

Figure 20 represents emergent profiles for the 4 Mg II lines in logarithmic scale.

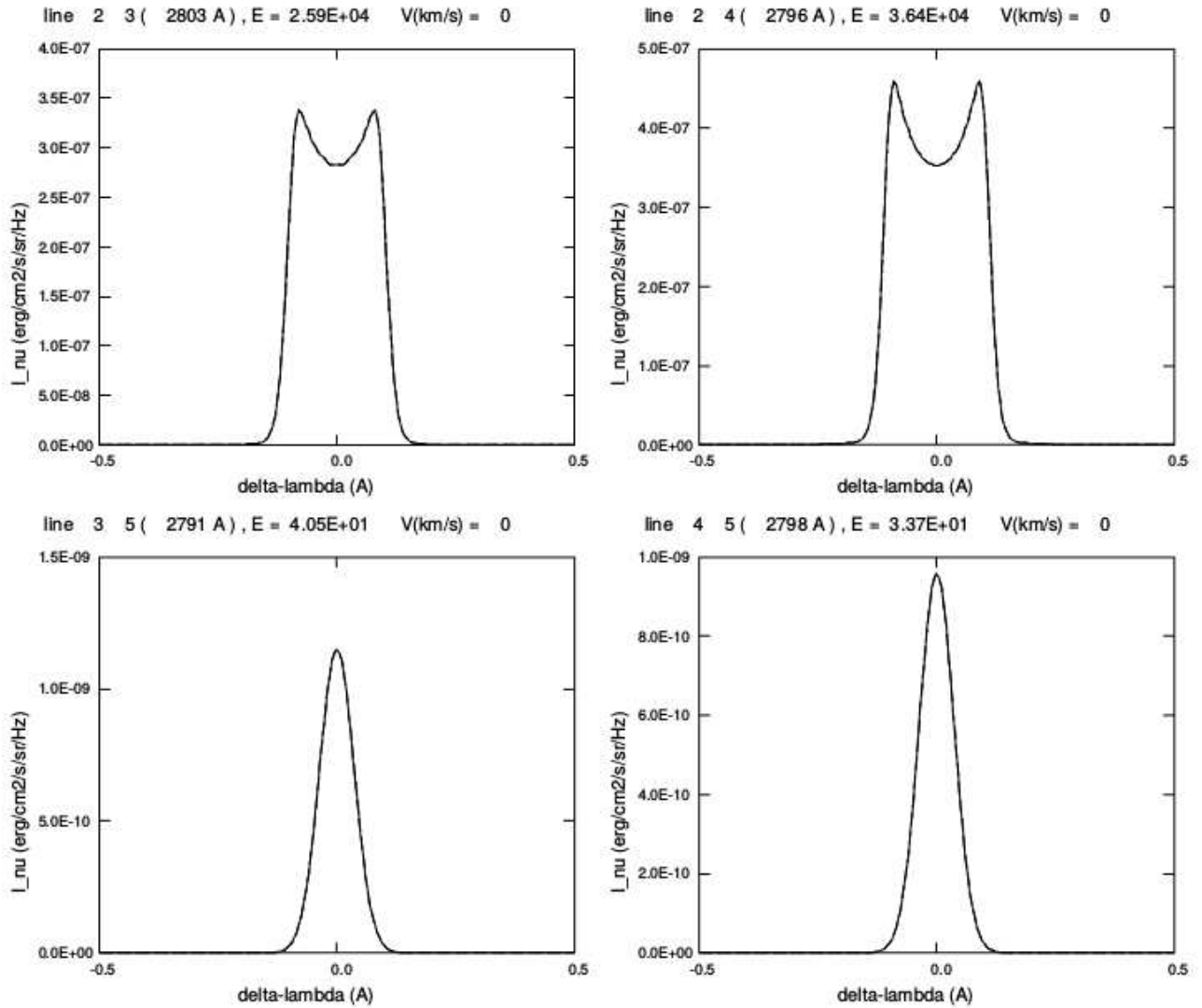


Figure 18: Line profiles (from left to right, from top to bottom) for h (2803 Å), k (2796 Å), 2791 Å, 2798 Å Mg II lines, for $V = 0$ km/s, without continuum absorption, for $\mu = 1$. Abscissa (Å), ordinate (erg/cm²/s/sr/Hz)

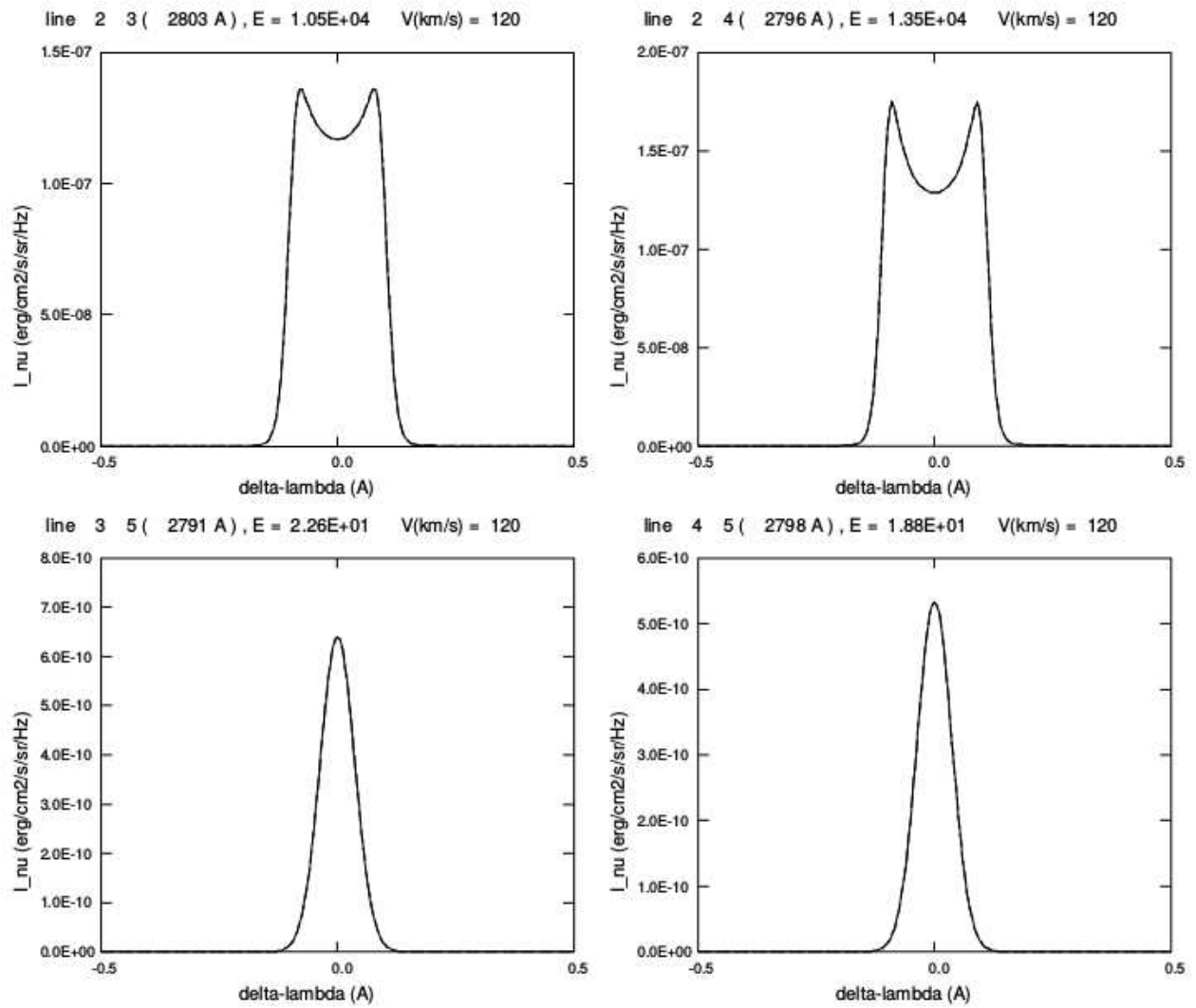


Figure 19: Line profiles (from left to right, from top to bottom) for h (2803 Å), k (2796 Å), 2791 Å, 2798 Å Mg II lines, for $V = 120$ km/s, without continuum absorption, for $\mu = 1$. Abscissa (Å), ordinate (erg/cm²/s/sr/Hz)

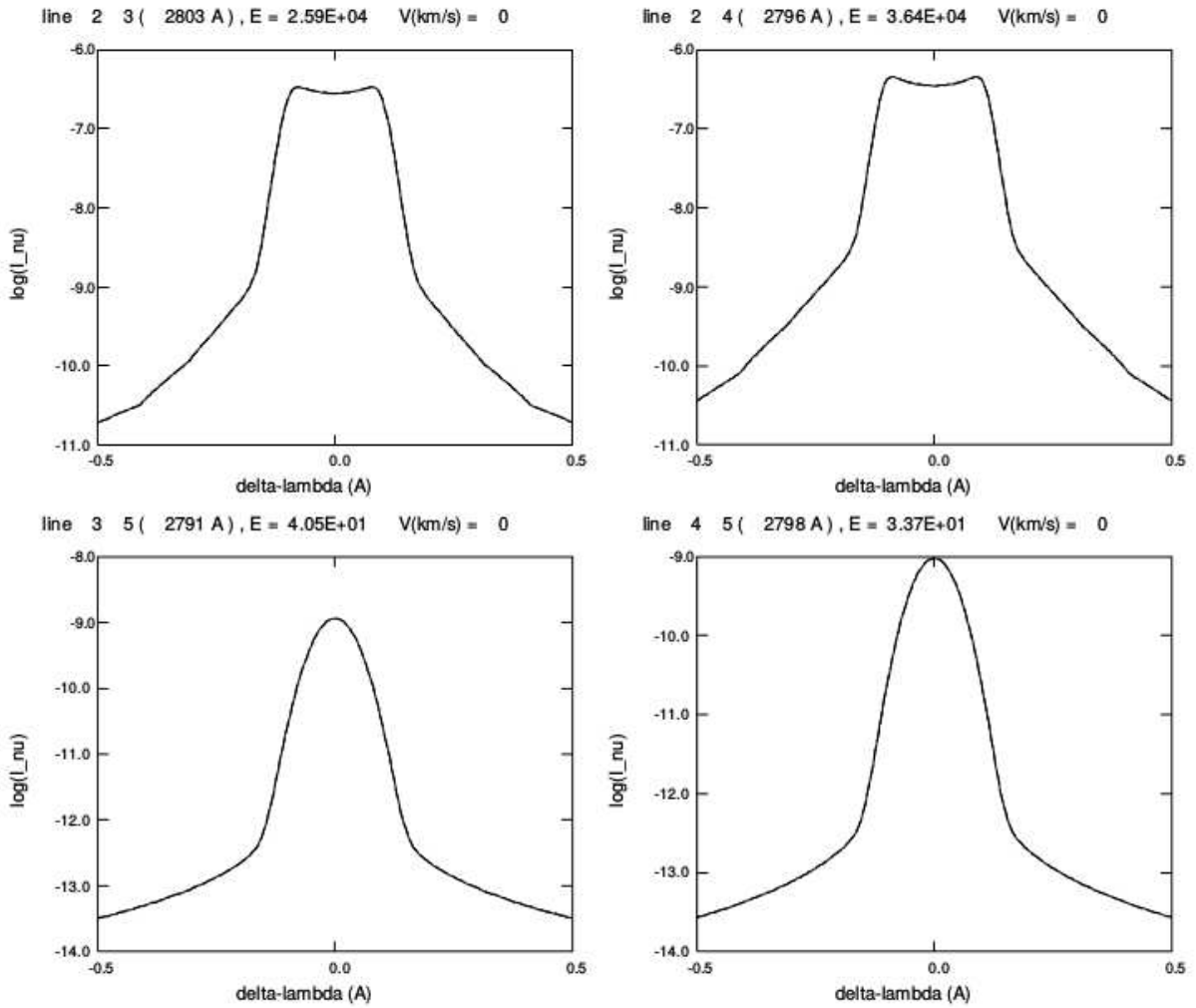


Figure 20: Line profiles (from left to right, from top to bottom) for h (2803 Å), k (2796 Å), 2791 Å, 2798 Å Mg II lines, for $V = 0$ km/s, in logarithmic scale, without continuum absorption, for $\mu = 1$. Abscissa (Å), ordinate ($\text{erg}/\text{cm}^2/\text{s}/\text{sr}/\text{Hz}$)

11 Running PRODOP

- Download the package source file PRODOP.tgz from MEDOC/TOOLS website: <https://idoc.ias.u-psud.fr/MEDOC/Radiative%20transfer%20codes>
- gfortran compiler is required. Type the following linux command:

- **tar -xvzf PRODOP.tgz**
- **cd PRODOP**
- The folder contains the following files: intica.dat (calcium incident intensities (half-profile). 1st column: frequency in Hz, 2nd column: intensities in $\text{erg/cm}^2/\text{s}/\text{sr}/\text{Hz}$), intinc_H.dat (hydrogen incident intensities (half-profile). 1st column: wavelengths in \AA , 2nd column: intensities in $\text{erg/cm}^2/\text{s}/\text{sr}/\text{Hz}$), intinc_He.dat (helium incident intensities (half-profile). 1st column: frequency in Hz, 2nd column: intensities in $\text{erg/cm}^2/\text{s}/\text{sr}/\text{Hz}$), intimg.dat (magnesium incident intensities (half-profile). 1st column: frequency in Hz, 2nd column: intensities in $\text{erg/cm}^2/\text{s}/\text{sr}/\text{Hz}$), model.dat, tem-bri.dat (1st column: wavelengths in microns, 2nd column: brightness temperatures for solar flux, on the entire disk, in K), makefile, prodop.f90, VIPRF.f90
- The file to modify is “model.dat”: the file contains 2 models defined by temperature (K), pressure (dyn/cm^2), thickness of the prominence/filament (km), microturbulence velocity (km/s), altitude of the prominence/filament relative to the sun’s surface (km) and bulk velocity (km/s). Depending on the IOEL value (i.e. of the atomic element considered), it will be necessary to adapt the copies of the output files fort.* and to comment on the atomic elements not used in the visualization program VIPRF.f90
- Run the code by typing:
 - make**
 - ./prodop**
- The output files are, for IOEL=2 : fort.10 (resume.dat), fort.21 (profilh.dat : H profile), fort.51 (profihe.dat : He profile), fort.81 (profica.dat : Ca profile), fort.91 (profimg.dat : Mg profile), fort.20 (fisuphy.dat : H incident intensities), fort.101 (fisupmg.dat : Mg incident intensities)
- cp fort.10 resume.dat
- cp fort.21 profilh.dat
- cp fort.51 profihe.dat
- cp fort.81 profica.dat
- cp fort.91 profimg.dat
- cp fort.20 fisuphy.dat
- cp fort.101 fisupmg.dat
- The folder **results** contains the output files corresponding to test cases to be able to check if your results are good

- Before running PRODOP again, type **make clean**
- To visualize the line profiles, we use the visualization program VIPRF.f90 by typing the following commands (modify in VIPRF.f90 the value of NMDL which is the number of models treated in model.dat):
- gfortran -o visu VIPRF.f90
- ./visu
- The output files are: profica.ps (Ca emergent profile), profihe.ps (He emergent profile), profilh.ps (H emergent profile), proinc.ps (H incident profile), profimg.ps (Mg emergent profile), pincmg.ps (Mg incident profile)

12 CPU time

For 2 atmosphere models with constant parameters (prominence case):

- $T = 8000$ K, $V = 5$ km.s⁻¹, $h = 10000$ km, $e = 1000$ km, $P = 0.01$ dyn.cm⁻², $V = 0$ km.s⁻¹
- $T = 8000$ K, $V = 5$ km.s⁻¹, $h = 10000$ km, $e = 1000$ km, $P = 0.01$ dyn.cm⁻², $V = 120$ km.s⁻¹

with the following options:

- IOEL = 4 (H+Mg)
- IOPCAC = 0 (without continuum absorption)
- IOPEAC = 0 (continuum absorption coefficients are not printed in the output file fort.66)
- IVHYD = 0 (list of hydrogen lines is not printed in the output file fort.66)
- IWRCR = 0 (radiative cooling rates are not printed)

On a PC with 4 processors (2.67 GHz):

- CPU time (2 models of protuberances mentioned above): 50 s < 1 min

13 Acknowledgements

We thank MEDOC directors: Eric Buchlin (present) and Frédéric Baudin (former).

30th March 2019

M. C-Y

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Ion model "name" MG11L2
 MAGNESM MG-I
 Abundance relative to Hydrogen 3.388E-05

Levels.....	Principal quantum number n	Rotational quantum number l	Number of "nl" electrons	Frequency Interval (peta-Hz)	Wavenumber (/cm)	Threshold wavelength (nm)	Statistical Weight
1	3	0	1	.6562712	21890	162.1507	1.
2	3	1	1	21890	21890		3.
3	3	2	1	1.65081	35051	162.1507	3.
4	3	3	1	1.235067	41197	162.1507	3.
5	4	0	1	1.394197	43503	162.1507	5.
6	4	1	1	1.391128	46403	162.1507	5.
7	4	2	1	1.43444	47847	162.1507	9.

HLP
 CP: Photoioniz. cross-section (cm**2)
 CI: Collisional ioniz. coefficient
 (as function of temperature)
 OIS (Xoe MGIT Subordinate)
 LCH: collisions-with-hydrogen code

Levels.....

8 9 10 11 12
 3 4 4 4 4
 1 1 1 1 1
 1 1 1 1 1

$T_{10} = (4 \cdot 10^3, 8 \cdot 10^3, 16 \cdot 10^3)$
 3^3

Frequency Interval (peta-Hz)	Wavenumber (/cm)	Threshold wavelength (nm)	Statistical Weight	CP: Photoioniz. cross-section (cm**2)	CI: Collisional ioniz. coefficient (as function of temperature)
1.437715	1.479377	1.624643	1.757291	1.781631	
47957	49346	54192	58616	59428	
729.183	811.4056	1.337E+03	3.274E+03	4.46E+03	
	15.	3.	15.	22.	26.
	3.42E-17	8.27E-18	4.19E-17	1.E-16	1.E-16
	2.18E-07	2.7E-07	7.33E-07	1.E-06	1.E-06
	2.81E-07	3.48E-07	9.46E-07	1.E-06	1.E-06
	3.33E-07	4.12E-07	1.12E-06	1.E-06	1.E-06
	3.77E-07	4.67E-07	1.27E-06	1.E-06	1.E-06
	4.87E-07	6.03E-07	1.64E-06	1.E-06	1.E-06
	1	1	1	1	1
Continuum Frequency Interval (peta-Hz)	1.84885				
Continuum wavenumber (/cm)	61671				

N O T E S

- * Parameter values = 0, and lines of all = 0, are normally omitted; to show them, set input parameter JZAT0M = 1.
- * The photoionization cross-section CP is the threshold value at the head of the continuum; for integrations over frequency, a nu**3 variation is assumed if explicit RRCP values (below) are not given. If the input value CP(1) = 0, then a default value is computed using Verner et al. (1996), ApJ 465, 487.
- List of ions with CP(1) and/or RRCP(1) data:
 HE1 HE2 B1 C1 C2 C3 C4 N1 N2 01 02 03 04 05 06 NA1 MG1 MG2 AL1 AL2
 S11 S12 S13 S14 S1 CA1 CA2 FE1 C5 N3 N4 NE1 NE2 NE3 ME4 NE5 NE6 NE7 NE8 NE9
 MA2 S2 S3 S4
- * RKMULT is used only when option RKINCR = on; in this run RKINCR = off.
- * CI-values are obtained as needed by interpolation in the tables printed above.
- * This run does not use any computed default values of CI.
- * Collisional ionization rates are computed from CI(T)*NE*exp(-h*NU/(k*T)), where NU is the threshold value at the head of the continuum.
- * Added to these rates for collisions with electrons are rates for collisions with hydrogen atoms, provided that ICHSW = 1 (here ICHSW = 1). For levels 2 and higher for which LCH = 1 the added rates are from B. Kaulakys, 1985, J.Phys.B, 18, L167. LCH(1), the LCH value for level 1, is an index explained in the

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Abundance relative to Hydrogen
 Atomic Mass
 Ion model "name"
 MAGNESIUM
 Mg-II
 24.3
 3.388E-05
 MG29L

Principal quantum number n
 Rotational quantum number l
 Number of "nl" electrons

Levels.....

	1	2	3	4	5	6	7
	3s ² 1/2	3p ⁴ 1/2	3p ³ 3/2	4s ² 1/2	3d ⁴	4p ⁴	3s ¹

Frequency Interval (peta-Hz)
 Wavenumber (/cm)
 Threshold wavelength (nm)

1	2	3	4	5	6	7
1.06934	1.07208	2.092699	2.14325	2.41783	2.78179	
35669	35760	68804	71491	80650	92790	
82.46452	116.8293	116.9542	194.3283	200.9115	246.2197	351.2008

Energy from Mg II 3s¹ level

ALP
 CP: Photoniz. cross-section (cm**2)
 CI: Collisional ioniz. coefficient
 (as function of temperature)

Statistical Weight

1	2	3	4	5	6	7
1.E+03	2.436E-19	1.E-17	1.E-17	1.E-17	1.E-17	1.E-17
1.20E+03	5.263E-08	1.219E-08	1.221E-08	2.768E-08	4.265E-08	5.199E-08
1.58E+03	2.953E-08	1.517E-08	1.521E-08	3.428E-08	5.275E-08	6.41E-08
2.E+03	2.274E-08	1.696E-08	1.7E-08	3.817E-08	5.867E-08	7.116E-08
2.51E+03	1.827E-08	1.885E-08	1.899E-08	4.223E-08	6.484E-08	7.846E-08
3.16E+03	1.524E-08	2.094E-08	2.098E-08	4.666E-08	7.155E-08	8.633E-08
3.98E+03	1.328E-08	2.321E-08	2.326E-08	5.14E-08	7.868E-08	9.464E-08
5.01E+03	1.212E-08	2.566E-08	2.571E-08	5.64E-08	8.615E-08	1.032E-07
6.31E+03	1.154E-08	2.827E-08	2.833E-08	6.162E-08	9.389E-08	1.121E-07
7.94E+03	1.138E-08	3.103E-08	3.109E-08	6.698E-08	1.017E-07	1.209E-07
1.E+04	1.153E-08	3.392E-08	3.399E-08	7.243E-08	1.096E-07	1.297E-07
1.259E+04	1.191E-08	3.689E-08	3.696E-08	7.784E-08	1.173E-07	1.381E-07
1.585E+04	1.245E-08	3.989E-08	3.997E-08	8.312E-08	1.246E-07	1.46E-07

OIS for bound-free
 transitions

OIS(6) OIS(7) OIS(8) OIS(9)

Temperature
 TRB = 6 * 10³, 8.10³, 10³

Levels.....	8	9
Principal quantum number n	4	4
Rotational quantum number l	2	3
Number of "nl" electrons	1	1

Frequency Interval (peta-Hz) 2.79739 2.81284
 Wavenumber (/cm)⁻¹ 93310 93799
 Threshold wavelength (nm) 357.7385 364.1036

Statistical Weight 10. 14.
 1.E-17 1.E-17
 CP: Photoioniz. cross-section (cm**2) 1.E+03 1.244E-07 1.456E-07
 CI: Collisional ioniz. coefficient (as function of temperature) 1.26E+03 1.379E-07 1.613E-07

1.58E+03 1.521E-07 1.778E-07
2.E+03 1.679E-07 1.961E-07
2.51E+03 1.839E-07 2.147E-07
3.16E+03 2.008E-07 2.342E-07
3.98E+03 2.182E-07 2.542E-07
5.01E+03 2.357E-07 2.742E-07
6.31E+03 2.531E-07 2.938E-07
7.94E+03 2.697E-07 3.126E-07
1.E+04 2.854E-07 3.3E-07
1.259E+04 2.996E-07 3.456E-07
1.585E+04 3.121E-07 3.589E-07
1.995E+04 3.224E-07 3.696E-07
2.512E+04 3.303E-07 3.774E-07
3.162E+04 3.358E-07 3.821E-07
3.981E+04 3.386E-07 3.838E-07
5.012E+04 3.39E-07 3.825E-07
6.31E+04 3.369E-07 3.783E-07
7.943E+04 3.326E-07 3.716E-07
1.E+05 3.262E-07 3.627E-07
1.259E+05 3.182E-07 3.518E-07
1.585E+05 3.086E-07 3.394E-07
1.995E+05 2.979E-07 3.257E-07
2.512E+05 2.862E-07 3.112E-07
3.162E+05 2.738E-07 2.961E-07
3.981E+05 2.61E-07 2.806E-07
5.012E+05 2.479E-07 2.651E-07
6.31E+05 2.346E-07 2.496E-07
7.943E+05 2.215E-07 2.343E-07
1.E+06 2.085E-07 2.194E-07
1.259E+06 1.957E-07 2.05E-07
1.585E+06 1.833E-07 1.911E-07
1.995E+06 1.714E-07 1.778E-07
2.512E+06 1.599E-07 1.652E-07
3.162E+06 1.488E-07 1.531E-07
3.981E+06 1.384E-07 1.418E-07
5.012E+06 1.284E-07 1.311E-07
6.31E+06 1.19E-07 1.21E-07
7.943E+06 1.101E-07 1.116E-07
1.E+07 1.017E-07 1.028E-07

Continuum Frequency Interval (peta-Hz)
Continuum wavenumber (/cm)

3.635411
121264

.....

N O T E S

Parameter values = 0, and lines of all = 0, are normally omitted; to show them, set input parameter JZATOM = 1.

* The photoionization cross-section CP is the threshold value at the head of the continuum; for integrations over frequency, a nu**3 variation is assumed if explicit RRCP values (below) are not given. If the input value CP(1) = 0, then a default value is computed using Verner et al. (1996), ApJ 465, 487.

List of ions with CP(1) and/or RRCP(1) data:

HE1	HE2	B1	C1	C2	C3	C4	N1	N2	O1	O2	O3	O4	O5	O6	NA1	MG1	MG2	AL1	AL2
SI1	SI2	SI3	SI4	S1	CA1	CA2	FE1	CS	N3	N4	NE1	NE2	NE3	NE4	NE5	NE6	NE7	NE8	NE9
MA2	S2	S3	S4																

* RKNMULT is used only when option RKNINCR = on; in this run RKNINCR = off.

* Values of CI(T) not specified in the input are computed by the program. Several methods are available for this purpose, as chosen by the user with the CIMETHOD input statement. Some or all of the CI-values of this run were computed using:

- Clark et al. 1991, ApJ 381, 597
- M. Arnaud & R. Rothenflug 1985, A&A 60, 425

level 1 only

* CI-values are obtained as needed by interpolation in the tables printed above.

* Collisional ionization rates are computed from $CI(T) \cdot N_E \cdot \exp(-h \cdot \nu / (k \cdot T))$, where ν is the threshold value at the head of the continuum.

* Collisions with hydrogen are controlled with input parameters LCH and IGHSW.

See also "About PANDORA", Section 5, Note 136.

* The raw computed default values of CI can be adjusted with MCI and ACI such that $CI(\text{adjusted}) = CI(\text{raw}) \cdot MCI + ACI$

The default values are: MCI = 1 and ACI = 0; only values differing from these are printed. Finally, all CI(adjusted) have been multiplied by the Reduction Factor for All Collisions, RFAC, such that $CI(\text{final default}) = RFAC \cdot CI(\text{adjusted})$; in this run RFAC = 1.099E+00.

>> More options and information for CI are given in Section 19 of "About PANDORA". The relevant control switch settings were printed in INPUT NOTES, above.

* To save the computed default parameter values in file .msc, turn option ATOMSAV on.

.....

Transitions.....	2/ 1	3/ 1	3/ 2	4/ 1	4/ 2	4/ 3	5/ 1
Line components							
Wavelength (nano-m)	280.3527	279.6362					
Wavenumber (/cm)	3569	35760					
Einstein A Value	2.575E+08	2.598E+08	[2.8E+01]	[3.3E+07]	1.173E+08	2.334E+08	[6.8E+06]
Oscillator strength	.3034203	.6091354			.1509177	.150953	

CE: Collisional Excitation Coefficient
(as function of temperature)

1.E+03	6.868E-07	1.374E-06	1.374E-06	2.62E-07	2.62E-07	1.31E-07	4.424E-07
1.26E+03	6.142E-07	1.228E-06	1.228E-06	2.269E-07	2.269E-07	1.134E-07	3.972E-07
1.58E+03	5.498E-07	1.099E-06	1.099E-06	1.954E-07	1.954E-07	9.771E-08	3.57E-07
2.E+03	4.926E-07	9.847E-07	9.847E-07	1.674E-07	1.674E-07	8.371E-08	3.211E-07
2.51E+03	4.42E-07	8.834E-07	8.834E-07	1.428E-07	1.428E-07	7.139E-08	2.891E-07
3.16E+03	3.973E-07	7.939E-07	7.939E-07	1.215E-07	1.215E-07	6.074E-08	2.604E-07
3.98E+03	3.578E-07	7.152E-07	7.152E-07	1.034E-07	1.034E-07	5.172E-08	2.347E-07
5.01E+03	3.232E-07	6.461E-07	6.461E-07	8.835E-08	8.835E-08	4.417E-08	2.115E-07
6.31E+03	2.928E-07	5.856E-07	5.856E-07	7.575E-08	7.575E-08	3.787E-08	1.906E-07
7.94E+03	2.663E-07	5.327E-07	5.327E-07	6.515E-08	6.515E-08	3.258E-08	1.718E-07
1.E+04	2.43E-07	4.863E-07	4.863E-07	5.608E-08	5.608E-08	2.804E-08	1.548E-07
1.259E+04	2.227E-07	4.455E-07	4.455E-07	4.823E-08	4.823E-08	2.412E-08	1.394E-07
1.585E+04	2.048E-07	4.097E-07	4.097E-07	4.149E-08	4.149E-08	2.074E-08	1.253E-07
1.995E+04	1.894E-07	3.788E-07	3.788E-07	3.575E-08	3.575E-08	1.787E-08	1.125E-07
2.512E+04	1.763E-07	3.527E-07	3.527E-07	3.088E-08	3.088E-08	1.544E-08	1.009E-07
3.162E+04	1.654E-07	3.31E-07	3.31E-07	2.677E-08	2.677E-08	1.338E-08	9.036E-08
3.981E+04	1.563E-07	3.13E-07	3.13E-07	2.329E-08	2.329E-08	1.164E-08	8.084E-08
5.012E+04	1.488E-07	2.982E-07	2.982E-07	2.033E-08	2.033E-08	1.016E-08	7.228E-08
6.31E+04	1.425E-07	2.857E-07	2.857E-07	1.78E-08	1.78E-08	8.898E-09	6.458E-08
7.943E+04	1.372E-07	2.749E-07	2.749E-07	1.562E-08	1.562E-08	7.812E-09	5.767E-08
1.E+05	1.324E-07	2.654E-07	2.654E-07	1.375E-08	1.375E-08	6.876E-09	5.148E-08
1.259E+05	1.281E-07	2.568E-07	2.568E-07	1.213E-08	1.213E-08	6.065E-09	4.594E-08
1.585E+05	1.241E-07	2.488E-07	2.488E-07	1.072E-08	1.072E-08	5.359E-09	4.099E-08
1.995E+05	1.204E-07	2.412E-07	2.412E-07	9.485E-09	9.485E-09	4.743E-09	3.656E-08
2.512E+05	1.167E-07	2.337E-07	2.337E-07	8.406E-09	8.406E-09	4.203E-09	3.261E-08
3.162E+05	1.13E-07	2.263E-07	2.263E-07	7.457E-09	7.457E-09	3.728E-09	2.908E-08
3.981E+05	1.092E-07	2.188E-07	2.188E-07	6.621E-09	6.621E-09	3.31E-09	2.593E-08
5.012E+05	1.054E-07	2.11E-07	2.11E-07	5.883E-09	5.883E-09	2.942E-09	2.312E-08
6.31E+05	1.014E-07	2.031E-07	2.031E-07	5.231E-09	5.231E-09	2.615E-09	2.061E-08
7.943E+05	9.737E-08	1.95E-07	1.95E-07	4.653E-09	4.653E-09	2.326E-09	1.837E-08

OIS for lines



OIS(1,2) OIS(1,3)

Temperature
TAB = (4.10³, 8.10³, 16.10³)

Line components	Wavelength (nano-m)	Wavenumber (/cm)	Einstein A Value	Oscillator strength	CE: Collisional Excitation Coefficient (as function of temperature)	Radiative half width (A)	van der Waals half width (A)	Stark half width (A)	Damping component selector	Frequency Redistribution	GMMA for P.R.D.																																																																										
1.E+06	9.319E-08	1.866E-07	1.866E-07	4.14E-09	2.07E-09	1.638E-08	1.259E+06	8.892E-08	1.78E-07	3.686E-09	3.686E-09	1.843E-09	1.46E-08	1.585E+06	8.459E-08	1.693E-07	1.693E-07	3.281E-09	3.281E-09	1.641E-09	1.301E-08	1.995E+06	8.023E-08	1.606E-07	1.606E-07	2.922E-09	2.922E-09	1.461E-09	1.16E-08	2.512E+06	7.589E-08	1.519E-07	1.519E-07	2.603E-09	2.603E-09	1.301E-09	1.034E-08	3.162E+06	7.159E-08	1.433E-07	1.433E-07	2.319E-09	2.319E-09	1.159E-09	9.214E-09	3.981E+06	6.736E-08	1.348E-07	1.348E-07	2.066E-09	2.066E-09	1.033E-09	8.212E-09	5.012E+06	5.922E-08	1.266E-07	1.266E-07	1.84E-09	1.84E-09	9.202E-10	6.524E-09	6.31E+06	5.922E-08	1.185E-07	1.185E-07	1.64E-09	1.64E-09	8.199E-10	6.524E-09	7.943E+06	5.534E-08	1.108E-07	1.108E-07	1.461E-09	1.461E-09	7.306E-10	5.814E-09	1.E+07	5.162E-08	1.033E-07	1.033E-07	1.302E-09	1.302E-09	6.311E-10	5.182E-09
5.37E-05	5.39E-05	8.633E-05	8.604E-05	7.38E-06	7.382E-06	01111	01111	Partial	Partial	-1.	-1.	1.45E-05	1.45E-05	2.128E-04	2.139E-04	1.026E-04	1.032E-04	01111	01111	Complete	Complete																																																																

Transitions..... 5/2 5/3 5/4 6/1 6/2 6/3 6/4

Line components	Wavelength (nano-m)	Wavenumber (/cm)	Einstein A Value	Oscillator strength	CE: Collisional Excitation Coefficient (as function of temperature)	Radiative	Blend(2)	Radiative	Blend(2)	(Thin)	(Thin)	(Thin)																																																																																											
1.E+03	1.934E-06	1.554E-06	2.67E-06	5.593E-08	2.131E-07	1.973E-07	3.043E-06	1.26E+03	1.735E-06	1.394E-06	2.326E-06	5.694E-08	1.955E-07	1.789E-07	2.564E-06	1.58E+03	1.559E-06	1.251E-06	2.026E-06	4.666E-08	1.789E-07	1.628E-07	2.526E-06	2.E+03	1.403E-06	1.125E-06	1.77E-06	4.295E-08	1.632E-07	1.486E-07	2.323E-06	2.51E+03	1.263E-06	1.013E-06	1.588E-06	3.969E-08	1.485E-07	1.358E-07	2.152E-06	3.16E+03	1.139E-06	9.134E-07	1.382E-06	3.674E-08	1.35E-07	1.24E-07	2.006E-06	3.98E+03	1.028E-06	8.246E-07	1.233E-06	3.396E-08	1.228E-07	1.129E-07	1.884E-06	5.01E+03	9.295E-07	7.45E-07	1.103E-06	3.121E-08	1.113E-07	1.021E-07	1.782E-06	6.31E+03	8.415E-07	6.734E-07	9.83E-07	2.842E-08	1.002E-07	9.166E-08	1.697E-06	7.94E+03	7.632E-07	6.088E-07	8.694E-07	2.56E-08	8.951E-08	8.161E-08	1.628E-06	1.E+04	6.938E-07	4.993E-07	6.639E-07	2.009E-08	6.947E-08	6.315E-08	1.541E-06	1.259E+04	6.33E-07	4.54E-07	5.742E-07	1.759E-08	6.061E-08	5.504E-08	1.524E-06	1.995E+04	5.36E-07	4.149E-07	4.941E-07	1.533E-08	5.275E-08	4.781E-08	1.523E-06

↑
OIS for lines

Line components	Wavelength (nano-m)	Wavenumber (/cm)	Einstein A Value	Oscillator strength	CE: Collisional Excitation Coefficient (as function of temperature)	Radiative	Blend(2)	Radiative	Blend(2)	(Thin)	(Thin)	(Thin)																																																																																											
1.E+03	1.934E-06	1.554E-06	2.67E-06	5.593E-08	2.131E-07	1.973E-07	3.043E-06	1.26E+03	1.735E-06	1.394E-06	2.326E-06	5.694E-08	1.955E-07	1.789E-07	2.564E-06	1.58E+03	1.559E-06	1.251E-06	2.026E-06	4.666E-08	1.789E-07	1.628E-07	2.526E-06	2.E+03	1.403E-06	1.125E-06	1.77E-06	4.295E-08	1.632E-07	1.486E-07	2.323E-06	2.51E+03	1.263E-06	1.013E-06	1.588E-06	3.969E-08	1.485E-07	1.358E-07	2.152E-06	3.16E+03	1.139E-06	9.134E-07	1.382E-06	3.674E-08	1.35E-07	1.24E-07	2.006E-06	3.98E+03	1.028E-06	8.246E-07	1.233E-06	3.396E-08	1.228E-07	1.129E-07	1.884E-06	5.01E+03	9.295E-07	7.45E-07	1.103E-06	3.121E-08	1.113E-07	1.021E-07	1.782E-06	6.31E+03	8.415E-07	6.734E-07	9.83E-07	2.842E-08	1.002E-07	9.166E-08	1.697E-06	7.94E+03	7.632E-07	6.088E-07	8.694E-07	2.56E-08	8.951E-08	8.161E-08	1.628E-06	1.E+04	6.938E-07	4.993E-07	6.639E-07	2.009E-08	6.947E-08	6.315E-08	1.541E-06	1.259E+04	6.33E-07	4.54E-07	5.742E-07	1.759E-08	6.061E-08	5.504E-08	1.524E-06	1.995E+04	5.36E-07	4.149E-07	4.941E-07	1.533E-08	5.275E-08	4.781E-08	1.523E-06

↑
Temperature
T_{AO} = (4.10³, 8.10³, 16.10³)

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