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Solar and Stellar Atmospheric Modeling Using the Pandora Computer Program

Eugene H. Avrett and Rudolf Loeser

Smithsonian Astrophysical Observatory, Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA
avrett,rloeser@cfa.harvard.edu

Abstract. The Pandora computer program is a general-purpose non-LTE atmospheric modeling and spectrum synthesis code which has been used extensively to determine models of the solar atmosphere, other stellar atmospheres, and nebulae. The Pandora program takes into account, for a model atmosphere which is either planar or spherical, which is either stationary or in motion, and which may have an external source of illumination, the time-independent optically-thick non-LTE transfer of line and continuum radiation for multilevel atoms and multiple stages of ionization, with partial frequency redistribution, fluorescence, and other physical processes and constraints, including momentum balance and radiative energy balance with mechanical heating. Pandora includes the detailed effects of both particle diffusion and flow velocities in the equations of ionization equilibrium. Such effects must be taken into account whenever the temperature gradient is large, such as in a chromosphere-corona transition region.

1. Introduction

In this paper we first present a description of four different types of model atmosphere calculations: radiative equilibrium, general equilibrium, semi-empirical, and hydrodynamical, followed by a brief discussion of the important effects that should be included in model calculations. Then we describe the Pandora program which can be used for many different purposes, but is restricted at present by the assumptions of one-dimensionality and time-independence. Pandora can be used for the first three types of model calculations but does not include the detailed time-dependent effects used in the hydrodynamic calculations. We list the publications that document the methods used in the program and that give the results of many different applications. The program is available to new users on request (with the caveat that it is an extensive general-purpose program that requires a significant commitment of learning time on the part of the user; see the Pandora webpage http://cfa-www.harvard.edu/∼rloeser/pandora.html).

2. Types of Model Atmosphere Calculations: An Overview

Model atmospheres can be classified as being of four general types: radiative equilibrium, general equilibrium, semi-empirical, and hydrodynamical. The first is based on the constraint of radiative equilibrium for which the temperature distribution is determined so that the outward radiative flux is constant with depth. Radiative equilibrium models assume that there are no sources of non-radiative heating, and are normally time-independent without mass flows. Except in special cases, the temperature decreases monotonically with decreasing depths. Examples are the deeper layers of stellar atmospheres (photospheres) that show no evidence of non-radiative heating effects. See Kurucz (1970, 1979, 1991, 1998).

General equilibrium models are usually time-independent but include the effects of non-radiative energy flow due to thermal conduction, particle diffusion, and mass flows, and can include mechanical heating specified in some parametric way. Examples are the thin transition regions between neutral and ionized regions where a very steep temperature gradient results from strong resonance-line cooling at the lower temperatures. See Fontenla, Avrett, & Loeser (2002).

Semi-empirical models use a prescribed temperature distribution which is selected to obtain agreement between the spectrum calculated from the model and an observed spectrum. From such a model one can use the calculated departures from constant radiative flux to infer the corresponding mechanical heating distribution. Examples are stellar chromospheres that show emission due to an outward increase in temperature caused by the dissipation of mechanical energy in some form. See Vernazza, Avrett, & Loeser (1981) and Avrett (2002).

Hydrodynamical models simulate dynamical processes and use their properties to supply the mechanical heating necessary to account for an observed spectrum that shows emission in excess of that determined by radiative equilibrium. Such hydrodynamical models must assume some initial conditions to get the gas motions started, but then the model relies on internal wave motions to produce the mechanical heating. The aim in such calculations is to include all important physical processes and to match the given observations well enough to have confidence that the simulation is realistic. The time-dependent hydrodynamical models cannot be expected to lead to good agreement with observations if any important physical processes are not included or are not treated correctly. To the extent that the hydrodynamical models agree with observations they tell us more about the physical mechanisms at work than can be learned from the semi-empirical models, since the latter can indicate only the general properties of the temperature and mechanical heating distributions yielding a given spectrum. In extreme cases the variations with time in hydrodynamical models can be very large, suggesting that time-averaged quantities in a corresponding time-independent semi-empirical model may not properly represent the physical conditions in the atmosphere. Examples are the dynamical solar atmospheric models of Carlsson & Stein (1997, 1999).

For a radiative equilibrium model one must specify the effective temperature (which measures the total radiative flux), the surface gravity, and the chemical composition of the atmosphere, and can then calculate a model atmosphere and the corresponding spectrum to compare with an observed stellar spectrum. In many cases, combinations of values of the effective temperature, gravity, and composition can be found that lead to good agreement between calculated and

observed spectra. However, if the observed spectrum shows emission features that cannot be explained with radiative equilibrium models, one can carry out general equilibrium calculations, or can change the radiative equilibrium temperature distribution to a semi-empirical distribution chosen by trial-and-error to give a best match between the calculated and observed spectra. The final alternative is to introduce wave motions that heat the atmosphere and to calculate a self-consistent time-dependent hydrodynamical model in an attempt to match the observed spectrum. The hydrodynamical calculations are complex, and the results reported to date by Carlsson & Stein match some observations well but fail to match others. See Kalkofen (2001).

3. Important Processes in Model Atmosphere Calculations

3.1. Atomic and Molecular Data

Consider the calculation of the spectrum of atomic hydrogen. A good representation of the hydrogen atom in most cases is one having 15 levels, with 105 line transitions. It is not possible to calculate the hydrogen spectrum without including the many other atoms, ions, and molecules that influence the lines and bound-free continua of hydrogen and that provide the dominant opacity contributions in various parts of the spectrum. These contributions include not only the negative hydrogen ion and the bound-free continua of He, C, Mg, Si, Al, Ca, Na, Fe, and other atoms, but vast numbers of line transitions from these and other atoms, ions, and molecules. All of these need to be represented in detail with many levels and transitions, and all interact with each other. Fortunately, most of these interactions can be treated iteratively with no intrinsic convergence problems. The model calculations of all four types require extensive multilevel atomic and molecular systems in order to calculate in detail the intensity of radiation as a function of both wavelength and depth. When LTE (see below) can be assumed, it is sufficient to include in the model calculation only the opacity due to all the lines and the various continua as functions of wavelength and depth (since the ratio of emission to absorption is then given by the Planck function). Extensive line-opacity tabulations are available on CD-ROMs from R. Kurucz (see `http://kurucz.harvard.edu`).

3.2. Non-LTE Effects

Radiative equilibrium models usually are calculated assuming local thermodynamic equilibrium (LTE), i.e., assuming that all atomic and molecular energy levels are populated at each depth as they would be in thermal equilibrium corresponding to the kinetic temperature at that depth. This is a good approximation for high-density regions at large optical depths where the radiation intensity at a given location is produced in a small surrounding volume and hence can be represented by the Planck function at the local temperature. But in low-density atmospheric regions where photons are likely to be scattered (i.e., re-emitted after an absorption with no intervening collisional transitions) the radiation is produced in a larger surrounding volume. If this volume extends into or beyond the surface layers, where there is little or no emission, the radiation intensity at the given location is usually smaller than that given by the

local Planck function. Such non-LTE effects are of critical importance in low-density atmospheric regions, such as in stellar chromospheres and higher layers. To account for non-LTE effects it is necessary to solve complicated systems of radiative transfer and statistical equilibrium equations. See Vernazza, Avrett, & Loeser (1973), Mihalas (1978), Anderson (1989), Avrett & Loeser (1992), Avrett (1996), and especially the proceedings of the recent Tübingen workshop on Stellar Atmospheric Modeling (Hubeny, Mihalas, & Werner 2002).

3.3. Partial Redistribution

The thermal motions of atoms which absorb and re-emit photons in a given line cause frequency redistribution within the narrow Doppler core of the line. In the far wings, however, frequency redistribution is limited and the scattering is essentially coherent. Complete frequency redistribution (CRD) over the entire line is a useful simplifying approximation, but one that is inappropriate for strong lines formed in low-density atmospheric regions.

The theory of partial frequency redistribution (PRD) is reasonably well understood and should be included for all strong lines. See the review of early developments by Linsky (1985), and the more recent papers by Cooper, Ballagh, & Hubeny (1989), Hubeny & Lanz (1995), and Uitenbroek (2001).

The CRD line source function is frequency-independent while the line source function determined from the more general PRD theory varies from core to wing. It is often important to include PRD interlocking between lines having an energy level in common, and between blended or partially overlapping lines (e.g., see Mauas, Avrett, & Loeser 1989), and to include the detailed effects of Doppler shifts due to relative gas motions.

3.4. Particle Diffusion and Advection

In atmospheric regions with steep temperature gradients, e.g., a chromosphere-corona transition region, three sources of heat flow should be considered: thermal conduction, particle diffusion, and, in the case of mass flows, advection (understood to include the ionization effects described below). Thermal conduction depends in a simple way on the temperature gradient.

In a partially ionized gas, ambipolar diffusion of ions (diffusing toward lower temperatures) and of atoms (diffusing toward higher temperatures) also depends on the temperature gradient, and is often more important than thermal conduction. The main heat flow contribution made by diffusion is the ionization energy carried by ions that recombine to release energy at lower temperatures.

Advection refers to the effects of mass and particle flow velocities. Flows toward lower temperature regions also cause ions to release their ionization energy at the lower temperatures and heat the gas, but this component of the heat flow does not depend on the temperature gradient. If roughly the same total heat flow toward lower temperatures is needed to balance the losses of energy by radiation, then the temperature gradient will be reduced in order to reduce the conduction and diffusion contributions. Conversely, given roughly the same radiative losses to be balanced, a flow toward higher temperature regions counteracts the opposite flow of heat carried by conduction and diffusion, so that the temperature gradient must be larger in order to enhance the conduction and diffusion contributions.

The profiles of the hydrogen and helium resonance lines formed in the solar transition region are greatly affected by diffusion and by flows, and Doppler line shifts are much less important than the asymmetric changes in line intensity and central reversal due to the influence of flows on excitation and ionization. These conclusions are based on our current reference model of the solar atmosphere that extends from the photosphere into the corona, and that is roughly in accord with the observed solar spectrum from radio waves to X-rays (Fontenla, Avrett, & Loeser 2002).

4. The Pandora Atmosphere Program: General Description

Pandora deals with a time-independent one-dimensional atmospheric region that is either finite or semi-infinite in the plane-parallel case, or that has spherical symmetry. The atmospheric layers can be stationary or can be moving relative to each other. Illumination from an external source can be prescribed at the atmospheric boundary (front or back in the finite case).

The basic calculation assumes a given temperature and density stratification. Typically a temperature distribution is prescribed and the density is determined assuming 1) hydrostatic equilibrium (balancing gas pressure and gravity), or 2) pressure equilibrium in the absence of gravity (or any other constraint). After the radiative properties of the atmosphere are calculated, a revised temperature distribution can be determined subject to energy balance constraints, using parameters that describe given non-radiative processes. For example, Avrett and Loeser (1988) in a study of quasar broad emission line regions calculated the internal structure and the emergent spectrum of a constant-pressure cloud of a given large optical thickness with given illumination incident upon one face. The temperature distribution in this case was determined from the constraint of radiative energy balance. This is an example of the general equilibrium type of calculation discussed above. A new temperature distribution also can be determined by trial-and-error to obtain agreement between the calculated spectrum and an observed one, thus obtaining a semi-empirical model.

Given the temperature and density distributions, the non-LTE energy level populations of the various atoms and ions can be calculated. In typical problems the line and continuum optical depths can reach very large values, but collisions between atoms and electrons are too infrequent to establish LTE except in the deepest layers. The statistical equilibrium equations determine the populations at any point in the atmosphere given the properties of the radiation at that point. According to the radiative transfer equation, the radiation at that point depends on the radiative sources and hence on the populations throughout a large surrounding volume. The set of coupled transfer and statistical equilibrium equations must be solved for both the populations and the radiative intensities at all points in the atmosphere. For a single line transition this can be called the two-level transfer problem. The general case of an atom or ion with many interacting line transitions can be called the multi-level transfer problem. These cases will be discussed further in the following sections. First, however, we consider some other parameters that need to be determined as part of the overall solution.

As the temperature changes throughout the atmosphere we may need to calculate the level populations of each successive ionization stage of a given element, e.g., Si-I, Si-II, Si-III, Si-IV, ..., and each of these stages may have a large number of discrete energy levels. For simplicity, Pandora treats, in any one computer run, the levels of a single ionization stage together with the lowest level of the next higher stage to determine the relative populations of these levels. The sum of the populations of these two stages is a certain fraction of the total element abundance. After calculating the populations for Si-I–II, assuming all silicon to be in these two stages, the subsequent Si-II–III calculation will then exclude the Si-I fraction, etc. The Si-I–II populations must then be redetermined by a calculation that excludes the fraction in Si-III and higher stages. Such iterations require several repeats to get consistent results. This approach assumes that ionization and recombination take place only between successive stages and not, e.g., between Si-I and Si-III.

The electron number density needed in these calculations depends on the ionization of various constituents. Consider the simple case in which the electron density $n_{\rm e}$ is the sum of the proton density $n_{\rm p}$ and the contribution $(Z\times n_{\rm H})$ from all other elements, where $n_{\rm H}$ is the total hydrogen density and Z, in the simplest case, is the fraction of those elements that are once ionized, thus contributing one electron. For hydrogen we can write $n_{\rm H} = n_{\rm HI} + n_{\rm p}$ (when molecular hydrogen can be ignored), and $n_{\rm HI} = b_1 n_{\rm e} n_{\rm p} \psi(T)$ where $n_{\rm HI} = n_{\rm e} n_{\rm p} \psi(T)$ is the LTE Saha-Boltzmann equation for the neutral hydrogen density (in the lowest level) and b_1 is the departure coefficient, or correction factor, obtained from the detailed non-LTE calculation for hydrogen. Eliminating $n_{\rm HI}$ and $n_{\rm p}$ gives a quadratic equation that can be solved for $n_{\rm e}$, given Z, $n_{\rm H}$, b_1, and T. The indirect dependence of Z and b_1 on $n_{\rm e}$ is treated iteratively.

The different ions (including neutral atoms) interact with one another not only through their contributions to $n_{\rm e}$ but also because the different ions influence and are influenced by the common radiation field which varies with wavelength and with location in the atmosphere. When solving for the populations of a given ion we need to know in detail how other ions absorb and emit radiation at the transition frequencies of the given ion. Pandora treats this dependence iteratively, including all important non-LTE effects. In the case of the Sun the non-LTE populations of H, H^-, He-I, He-II, C-I, Si-I, Mg-I, Fe-I, Al-I, Ca-I, and Na-I are computed to determine $n_{\rm e}$ and the observed continuum, and the influence of the very large number of lines in the spectrum is considered when calculating photoionization rates. For this purpose Pandora uses a sampled set of Kurucz's line opacities (see Avrett, Machado, and Kurucz 1986).

5. The two-level transfer problem

Consider a line transition involving levels 1 and 2. Ignoring absorption and emission by other sources and ignoring stimulated emission for simplicity, the radiation intensity at a given location results from the emission and absorption at every frequency. The radiative transfer equation for frequency ν in the line is

$$\frac{dI_\nu}{dz} = \frac{-h\nu}{4\pi}\phi_\nu(n_1 B_{12} I_\nu - n_2 A_{21}), \tag{1}$$

where B_{12} and A_{21} are the Einstein coefficients for absorption and spontaneous emission, z is geometrical distance measured in the direction of the radiation intensity I_ν, n_ℓ represents number density of level ℓ, and ϕ_ν is the normalized absorption profile that includes the effects of Doppler broadening near line center and other types of broadening in the wings. Here for simplicity we have assumed that the emission profile is also ϕ_ν so that the absorbed and emitted photons are uncorrelated; this is the assumption of complete frequency redistribution (CRD). When a line such as the hydrogen Lα line has substantial opacity in the wings, and when the perturbing densities are low, then the absorption of a photon in the wings is followed by the re-emission of a photon with a frequency that is likely to be close to that of the absorbed photon, rather than a frequency near line center; this is the more general case of partial frequency redistribution (PRD). Pandora allows any line to include PRD effects (see Vernazza, Avrett, and Loeser 1981 and Avrett and Loeser 1984).

Using CRD as in equation (1), we introduce the monochromatic optical depth τ_ν (again in the direction of I_ν), and write

$$\frac{dI_\nu}{d\tau_\nu} = -I_\nu + S, \tag{2}$$

where S is the line source function

$$S = \frac{n_2}{n_1}\frac{A_{21}}{B_{12}} \tag{3}$$

(without stimulated emission). In the simple case of only radiative and collisional transitions between levels 1 and 2 (and no continuum), the statistical equilibrium equation is

$$0 = n_1(B_{12}\overline{J} + C_{12}) - n_2(A_{21} + C_{21}), \tag{4}$$

where

$$\overline{J} = \int \phi_\nu J_\nu d\nu \tag{5}$$

and where the mean intensity is given by

$$J_\nu = \frac{1}{4\pi}\int I_\nu d\Omega. \tag{6}$$

One can solve equation (2) for I_ν in terms of S and express the result as

$$I_{ik} = \sum_j \Lambda_{ijk} S_j, \tag{7}$$

where i and j are depth indices between 1 and N_D and k is the frequency index. Here the integral has been approximated by the sum of the values of S weighted by appropriate coefficients. These Lambda-operator weighting coefficients depend only on the values of τ_{ik} and on the choice of formal approximation of the variation of $S(\tau_\nu)$ between one value of τ_ν and the next. Several different functional representations are available in Pandora; the choice we find works best is simply to approximate S in the interval $\tau_{i-1,k} \leq \tau \leq \tau_{i+1,k}$ by the parabola

through $S(\tau_{i-1,k})$, $S(\tau_{i,k})$, and $S(\tau_{i+1,k})$, $i \neq 1, N_D$, and linearly in all other intervals.

Combining equations (5) – (7) gives

$$\overline{J}_i = \sum_j W_{ij}^{\Lambda} S_j. \tag{8}$$

The statistical equilibrium equation (4) can be written in terms of S as

$$S_i = \frac{\overline{J}_i + \epsilon B_i}{1 + \epsilon}, \tag{9}$$

where $\epsilon = C_{21}/A_{21}$ and $B_i = (2h\nu^3/c^2)\exp(-h\nu/kT_i)$ (the Planck function without stimulated emission). Combining equations (8) and (9) gives a set of simultaneous equations for S at each depth.

This is basically the way the two-level problem should be solved when ϵ is very small. Normally over $1/\epsilon$ iterations would be required to obtain a solution by alternately evaluating equations (8) and (9), i.e. by iterating between the radiative transfer and statistical equilibrium equations. Accelerated Lambda Iteration (ALI) techniques have been developed that allow this iterative approach to succeed (see Rybicki & Hummer 1991, 1992, Heinzel 1995, and the review by Avrett 1996). For a single transition we have found that solving the set of simultaneous equations is faster than ALI. For multilevel cases (discussed below) however, ALI is usually much faster because ALI can take account of the interactions between transitions while computing the iterative solutions for each transition.

6. The multi-level transfer problem

When there are many radiative transitions in the model atom, equations (8) and (9) still can be applied to each transition, but ϵ and B now take a more general form based on all transition pathways between the upper and lower levels of the given transition, apart from the direct radiative transition. Pandora is based on such a generalization of the two-level solution. Since the ϵ and B terms for a given radiative transition depend on the solutions of other radiative transitions, one must iterate on these terms even though the solution for each transition, given ϵ and B, is exact. The advantage of this method is that the individual solutions show the causes of calculated results (e.g., why a given source function has a particular variation with depth). The disadvantage is that this method generally requires more computing than other methods developed in recent years.

As explained above, Pandora combines the radiative transfer and the statistical equilibrium equations for a given radiative transition into sets of simultaneous equations, one such set for each of the N_D depth points of the atmosphere. For a model ion with N_L levels and a continuum, we have N_L statistical equilibrium equations analogous to equation (4). For a model ion with N_T transitions there are N_T sets of simultaneous equations that must be solved. (If every radiative transition between N_L levels is treated in the ion model, then $N_T = N_L(N_L - 1)/2$.) These calculations must be repeated iteratively because the ϵ and B terms for one radiative transition depend on the other radiative

transitions. Solving N_T sets of simultaneous equations for N_D depths for many iterations can require much computing. However, it is rarely necessary to solve all these sets of simultaneous equations (i.e., to compute a "full solution") for each of the N_T radiative transitions of a particular model ion. For all but the relatively strong line transitions it is sufficient just to let Pandora iterate between equations (8) and (9), i.e., just to carry out "Lambda iterations" for the relatively weak transitions. For other, often faster, methods in current use, see the papers in Hubeny, Mihalas, & Werner (2002).

7. Non-local statistical equilibrium (non-LTE)

We have also incorporated velocity terms in the Pandora statistical equilibrium equations, so that equation (4) would be written as

$$-\frac{d}{dz}(n_1 V) = n_1(B_{12}\overline{J} + C_{12}) - n_2(A_{21} + C_{21}) \tag{10}$$

to take account of the effect of a mass velocity V (increasing in the direction of the z coordinate). The derivative term causes n_1 at each depth to depend on n_1 at other depths, so that we use a finite difference procedure to solve the differential equation for $n_1(z)$ assuming given values for the other terms, including n_2. Then we evaluate

$$G = \frac{1}{n_1}\frac{d}{dz}(n_1 V), \tag{11}$$

and finally write equation (8) as

$$0 = n_1(B_{12}\overline{J} + C_{12} + G) - n_2(A_{21} + C_{21}), \tag{12}$$

which is then solved as before. In this way an advection term has been introduced into the equations of statistical equilibrium. (The Doppler shift due to mass flow is also included in the line absorption profile calculations.) The term on the left side of equation (10) is more important for ionization than for excitation (i.e., when n_2 represents the ion density rather than excitation level 2).

We also include particle diffusion velocities when there are steep temperature and ionization gradients. The hydrogen atom and proton diffusion velocities are given by $V_{\rm H} = [X/(1+X)]V_A$ and $V_{\rm p} = -[1/(1+X)]V_A$ where X is the ionization fraction $n_{\rm p}/n_{\rm HI}$ and

$$V_A = D_X\frac{d}{dz}(\ln X) + D_T\frac{d}{dz}(\ln T) \tag{13}$$

is the ambipolar diffusion velocity. The coefficients D_X and D_T are functions of the local number densities and the temperature, respectively. The diffusion velocity enters the calculation in the same way as the mass flow velocity except that hydrogen atoms and protons diffuse in opposite directions. See Fontenla, Avrett, & Loeser (1990, 1991) for details.

8. Implementation

Rather than going through the calculations in a fixed way, Pandora assumes a hands-on approach by the user. There are many input switches for specifying 1) alternative methods for specific calculations, 2) amounts of printout, 3) levels of printout detail, and 4) auxiliary output files (for use by other programs needing various Pandora-computed quantities). The user need not specify any of these options, alternative methods, or numerical control parameters at the start of a new calculation because Pandora provides defaults for all of them. There now exists a collection of atomic data input files for model ions of general interest; in many cases more than one version of a given ion is available, ranging from abbreviated to detailed models.

Pandora proceeds by iterating. It computes a specified number of grand iterations and then stops, having saved in various disk files all the data needed to resume the calculation for another specified number of iterations. Thus the evolving solution can be supervised closely and various control parameters and choices of method can be adjusted for optimal progress.

The computational properties of some of the procedures Pandora uses for various steps in the calculation have not been studied in detail for all types of applications. What has worked well for specific calculations in the past may not work well when applied to new, different regimes. We have provided many input control parameters to try to prevent unreasonable numerical behavior.

For some steps in the calculation, e.g. the evaluation of the Λ_{ijk} coefficients in equation (7), Pandora provides a menu of different methods that have been found to be well suited for specific situations. In each case the user can specify which method to use. We have begun to document what we have learned about the advantages and disadvantages of these alternatives, to help others choose.

9. Documentation

There are four sources of information about the program. 1) The Pandora printout is intended to be reasonably self-explanatory. There are printing options that allow the details of almost any calculation to be printed so that any step can be studied or verified. 2) A User's Guide is available that lists all input parameters, program options, and program outputs, along with extensive explanations of parameters and options. We continue to add material to this Guide. 3) The basic Pandora documentation, begun 36 years ago in October 1966, now consists of over 3400 pages of handwritten program notes specifying every program change or addition. Finally, a readily accessible source of information consists of 4) the derivations and explanations included in the following publications:

Avrett, E. H., & Loeser, R. 1969, Formation of line and continuous spectra. I. Source-function calculations, Smithsonian Astrophys. Obs. Spec. Rept. No. 303, 99pp

[Complete derivation of the two-level and multi-level statistical equilibrium and transfer equations, with integral operators used for the formal solution of the transfer equation.]

Avrett, E. H. 1971, Solution of non-LTE transfer problems, J. Quant. Spectrosc. Radiat. Transfer, 11, 511-529

[Basic formulation and discussion of non-LTE computational methods.]

Vernazza, J. E., Avrett, E. H., & Loeser, R. 1973, Structure of the solar chromosphere. I. Basic computations and summary of results, ApJ 184, 605-631

[Derivation of the equations of statistical equilibrium and radiative transfer for lines and the hydrogen Lyman-continuum; electron number density, hydrostatic equilibrium, and H^- non-LTE equations.]

Vernazza, J. E., Avrett, E. H., & Loeser, R. 1976, Structure of the solar chromosphere. II. The photosphere and the temperature-minimum region, ApJS 30, 1-60

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Vernazza, J. E., Avrett, E. H., & Loeser, R. 1981, Structure of the solar chromosphere. III. Models of the EUV brightness components of the quiet Sun, ApJS 45, 635-725

[Derivation of the energy balance equations, Lα partial redistribution, supplementary levels in the statistical equilibrium equations and in the Lyman-continuum transfer equation. Continuum data calculations for wavelengths 40 nm – 3 cm.]

Avrett, E. H., and Loeser, R. 1984, Line transfer in static and expanding spherical atmospheres, in Methods in Radiative Transfer, ed. W. Kalkofen (Cambridge: Cambridge Univ. Press), 341-379

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[Derivation and discussion of the equivalent two-level atom method of solving multi-level problems, with tabulated numerical solutions.]

Avrett, E. H., & Loeser, R. 1988, Radiative transfer in the broad emission-line regions of quasi-stellar objects, ApJ 331, 211-246

[Energy-balance non-LTE model atmosphere calculations with incident radiation, heavy-element cooling, and X-ray absorption.]

Mauas, P. J., Avrett, E. H., & Loeser, R. 1988, Mg-I as a probe of the solar chromosphere, ApJ 330, 1008-1021

[Includes a discussion of how to combine multiplet transitions in a simple way.]

Luttermoser, D. G., Johnson, H. R., Avrett, E. H., & Loeser, R. 1989, Chromospheric structure of cool carbon stars, ApJ 345, 543-553

[Modeling of N-type carbon stars with PRD calculations of the Mg-II lines.]

Mauas, P. J., Avrett, E. H., & Loeser, R. 1989, Computed profiles of the C-I multiplets at λ1561 and λ1657, ApJ 345, 1104-1113

[Partial frequency redistribution in multiplet lines.]

Fontenla, J. M., Avrett, E. H., & Loeser, R. 1990, Energy balance in the solar transition region. I. Hydrostatic thermal models with ambipolar diffusion, ApJ 355, 700-718

[Derivation of the effects of hydrogen ambipolar diffusion on the hydrogen number density calculations and on energy transport.]

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[Detailed set of flare model calculations using Pandora.]

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[Calculation of solar He-I and He-II lines.]

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