Non-LTE radiative transfer codes (1D and 2D) in solar and stellar structures

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Introduction

- For more than 30 years, numerical codes for Non-LTE radiative transfer have been developed at IAS. They are dedicated to various solar structures (prominences, filaments, chromospheres, ...) and stellar structures. Different geometries are considered : 1D, 2D cylindrical. Radiative transfer (Feautrier method) is computed both for continua and for lines belonging to various atomic systems (H, He, Mg, Ca, Fe, Ni) and velocity fields are also included. These codes have already been extensively used for **SOHO**, and more recently for **AIA/SDO** images and **IRIS** spectra.
- A set of codes from IRAP in 1D and 2D cartesian geometries including modern numerical methods (MALI: Multilevel Accelerated Lambda Iteration / Gauss-Seidel / Multi-grid method combined with the method of short characteristics) now validated numerically are also available at MEDOC, in preparation of the analysis of **Solar Orbiter** and future missions.
- Codes, documents and test cases can be found on the **MEDOC** website: https://idoc.ias.universite-paris-saclay.fr/MEDOC/Radiative transfer codes

Theoretical models (IAS codes)

Atomic line intensities and profiles are used to diagnose solar structures. To compute radiative transfer inside these lines, it is necessary ([1], [2], [3]) to:

1. **build** a **good atomic model** corresponding to the different atoms and ions responsible of line formation, as well as plasma parameters (electron density and temperature), external radiation field, ... Statistical equilibrium equations of atomic levels are solved including all available atomic data.
2. **describe** the considered **solar structures**. Different geometries can be used: 1D, 2D, ...
3. **solve radiative transfer equations** coupled to **statistical equilibrium**. This is done iteratively using hydrogen level populations obtained without radiation field as starting values. The computation of minor elements is performed after the electron density is determined from H (and He) ionization equilibrium.

1D slab and 2D cylinder geometries (IAS codes)

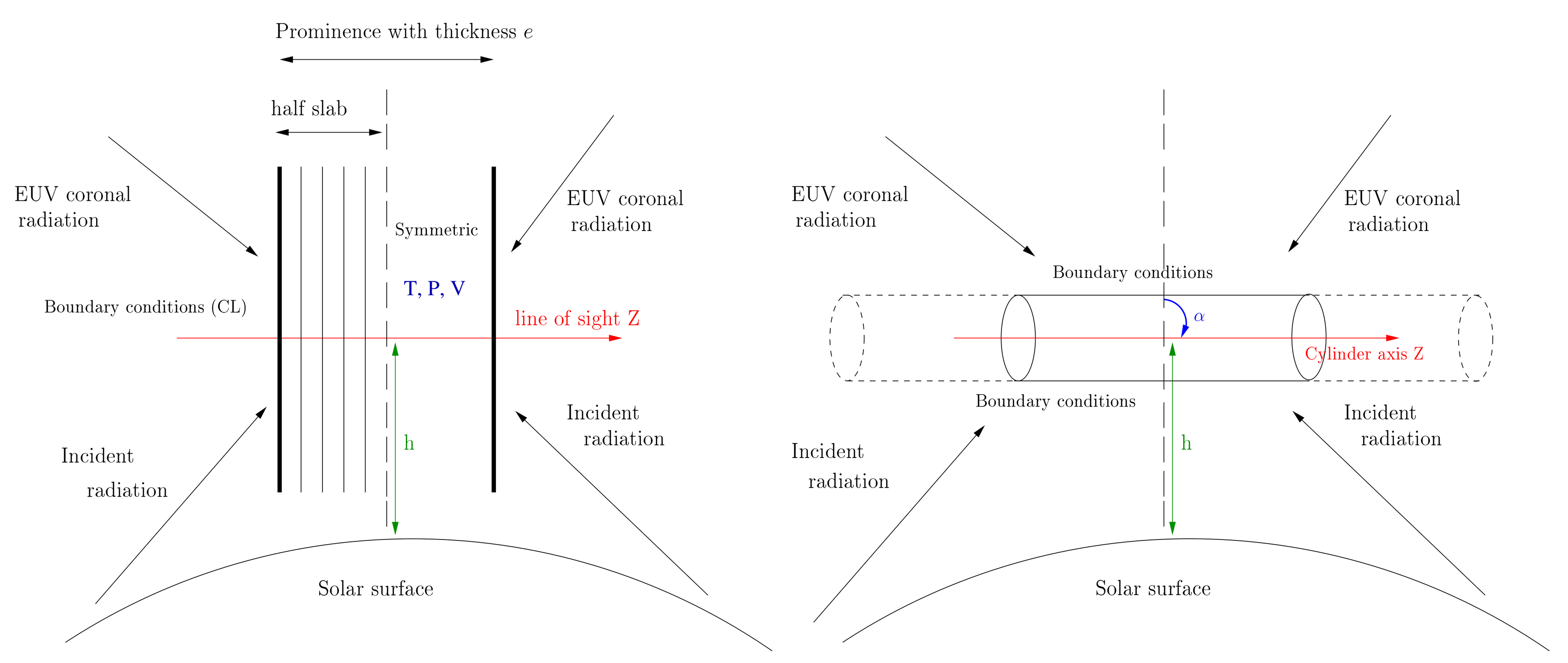

Figure 1:1D geometry (left), 2D cylinder geometry (right)

IAS codes description

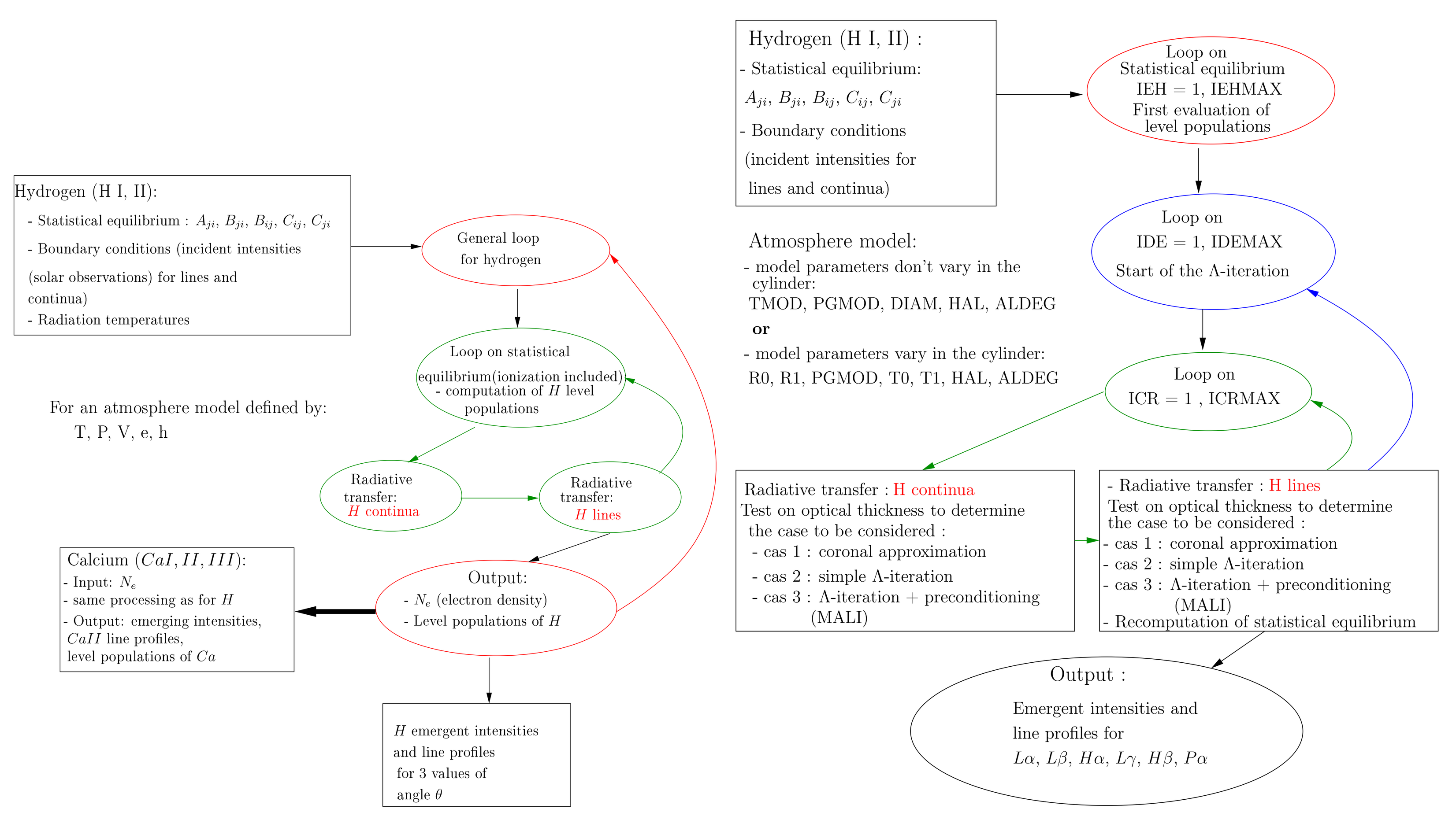

Figure 2:Algorithms: 1D (PROM7, on left) and 2D (CYMA2DV, on right)

Summary of available codes at MEDOC

- PROM5: 1D prominence model with profiles of varying physical properties across the prominence (H)
- PROM7: 1D prominence/filament, isobaric-isothermal atmosphere model (H, Ca)
- HYDR_NV/ATSTHS: 1D **semi-infinite atmosphere** (H, Mg, Ni, Na, Fe)
- PRODOP: 1D prominence model with velocity field (H, Ca, Mg, He)
- CYMA2DV: 2D cylinder model with velocity field (H)
- C2D2E: 2D cylinder model (H, He)
- Tools for Non-LTE radiative transfer (1D) can be used to construct new models using modern numerical methods
- H3CRD: 1D **semi-infinite atmosphere** (H). MALI combined with the method of short characteristics is used to solve multilevel non-LTE radiative transfer
- MALI and Gauss-Seidel: 2D prominence (H, He). Multilevel non-LTE radiative transfer solved either by MALI or by a Gauss-Seidel iterative scheme on a 2D Cartesian grid
- NLTE2D: 2D prominence (H). Multilevel non-LTE radiative transfer solved by MALI, Gauss-Seidel, and Successive Over-Relaxation (SOR) iterative schemes in 2D, together with a multi-grid algorithm, combined with the method of short characteristics in Cartesian geometry.

The last three codes allow easy implementation of additional lines, e.g. lines observed by Solar Orbiter instruments. This work is in progress.

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