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Structure and components of an LTE stellar atmosphere model

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Abstract. We summarize in this paper the principles for the algorithmic representation of the structure of a stellar atmosphere. The physical analysis of the problem leads to the classification of the elementary blocks that constitute a stellar atmosphere model and suggest the numerical algorithms required for its computation. Compatibly with the space allotted, we review our progress in the treatment of the basic components of an LTE stellar atmosphere model, and show a significant preliminary result.

Key words. stars: LTE atmosphere models - radiative transfer

1. Foreword

Pherhaps it will be not redundant to start recalling the twofold aim of stellar modelling: on the one hand, to describe the *structure* of the outermost layers of a star in terms of the radial distribution of the fundamental physical magnitudes; on the other hand, to compute synthetic spectra suitable for the *diagnostics* of the overall physical and chemical properties of a star by comparison with the spectrograms observed.

The wealth of observations at high spectral, spatial and time resolution, accumulated during the last two decades, has disclosed novel and complex aspects of stellar atmospheres that not only can yield new tools for diagnostics, but also suggest that the structure of the outermost layers is more complex than that usually considered by classical models. Hence the quest for a next generation of stellar atmosphere models, brought about by a thorough revision of their three basic ingredients: physics, atomic data and algorithms.

With regard to the physical content, we must make a difference between standard models (zero-order models) that take into account only the essential physics, and non-standard (higher order) models that include a wider gamut of more sophisticated phenomena.

A better knowledge of the atomic data is of course necessary, but this task lies out of the scope of the present work, which is chiefly oriented towards the algorithms.

On the computational side, the quite obvious remark that smart techniques should always replace a brute force approach becomes a call for qualitative improvements of the algo-

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rithms employed. Modern computers can offer much more than just high computational speed and huge memory storage. In order to take full advantage of these capabilities, we shall seek for novel algorithms, instead of conform ourselves with the implementation of classical numerical methods.

2. Structure and building blocks of a stellar atmosphere

The structure of a system, whose properties do not vary with time, is the result of a steady-state equilibrium among physical processes. Such a structure will be described in terms of the values of the fundamentals variables, determined at each point by the laws of conservation and the equation of state, as well as by the total amount of the internal energy of the system and the constraints imposed by initial and boundary conditions.

In the specific case of a stellar atmosphere, the gravitational confinement of the system is expressed by a condition of global *mechanical* equilibrium. The interchange of energy between the stellar material and the radiation field that permeate the latter is constrained by the condition of global *energy* equilibrium. These two conditions of equilibrium are coupled by means of the equation of state.

But the fundamental evidence of a net outward flux of radiative energy from the outermost stellar layers implies that the energy balance includes one component at least that cannot be considered in equilibrium. Hence the equilibrium equations and the equation of state must be supplemented by those that account for *radiative transfer*. Moreover, in many cases *convective* transport can occur in form of turbulent motions.

Transport phenomena make stellar atmospheres modelling to result in a very difficult mathematical problem for two reasons. On the one hand there is a strong correlation among the values of the physical variables at points widely apart, due to the great mean-free-path of the photons: *non-local* problem. On the other hand, the coefficients of the transport equations are determined by the local values of the fundamental variables that depend on the local density of photons, which in turn is determined by the solution of the transport equations: *non-linear* problem.

Our novel solution to the stellar atmosphere problem consists in the *Structural Iterative Approach* that we have presented elsewhere (Crivellari and Simonneau 1991; Crivellari 2002).

3. Basic components revisited

a) Radiative transfer

In the last years we have developed a novel algorithm, the Implicit Integral Method (IIM), for the numerical solution of the radiative transfer (RT) equation. The IIM has been exhaustively presented in a previous series of papers (Simonneau and Crivellari 1993; Crivellari and Simonneau 1994; Simonneau and Crivellari 1994; Gros et al. 1997). The most outstanding feature of the IIM comes from its algoritmic structure, that does not require any matrix formalism. The final product of our reserch work is an efficient, robust and reliable routine for monochromatic radiative transfer, that can be strightforwardly implemented into more general codes for specific RT problems. The advantage for modelling purposes is self-evident: no limitation is set *a priori* on the number of depth, direction and frequency points required by any specific RT problem.

b) A new formulation of the equation of state

We have reformulated the equation of state (EOS) for LTE plasmas and stellar atmospheres. The analytical results are the populations of the different ionization stages, the specific heats, the adiabatic gradient ∇_{ad}, the thermal dilatation coefficients, the speed of sound in the medium and the mean molecular weight (Cardona et al. 2002a). From the analytical expression we obtain next reliable numerical results (Cardona et al. 2002b).

c) Computation of the convective flux

On the basis of the results yielded by the new formulation of the EOS, we can compute the convective flux H_c, by taking into account

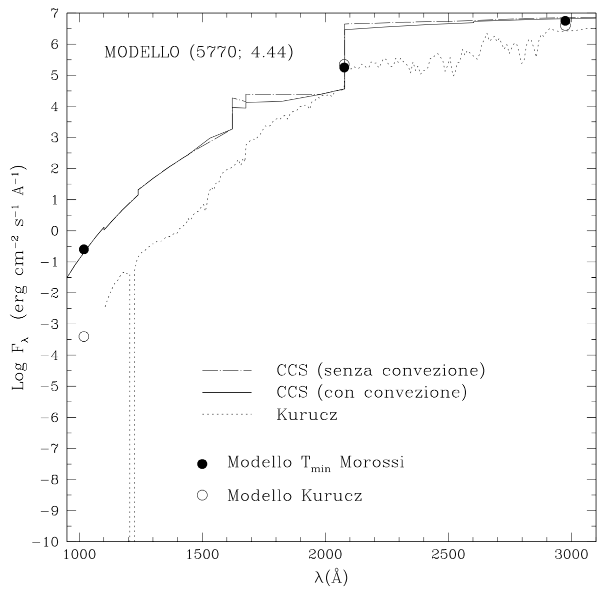

Fig. 1. The emergent flux F_λ of a solar model in the range 1000 − 3000 Å. The results of Cardona, Crivellari and Simonneau (CCS) are compared with those computed according to Kurucz. The full dots refer to a semi-empirical model furnished by C. Morossi (see Franchini et al. 1998).

for the moment ∇_{ad} as the gradient of the convective elements. The next step will be to include the radiative dissipation of energy into the computation of H_c.

d) A new approach to the computation of the energy balance

In cool (or even mildly cool) stars the integrals that account for the energy gains and losses at the Lyman frequencies (lines and continuum) overwhelm the contributions brought about by the other spectral ranges. Due to the large opacity of the former frequencies at all the layers somewhat deep, the monochromatic mean intensity J_ν equals numerically the corresponding source function S_ν. Thus the amount of energy absorbed at these frequencies results almost equal in practice to the amount of energy emitted. However, although it may be actually very small, itis this difference that determines the temperature distribution. The lack of accuracy of the computation can then falsify the energy balance. We have shown (Cardona et al. 2002c) how to get rid of this otherwise fatal drawback by solving the RT equations in the new variable $J_\nu - S_\nu$.

e) Temperature correction for an LTE model

The assemblage of the above pieces of work brought about a very efficient iterative scheme to correcting the temperature distribution for an LTE model. The method is presented in detail elsewhere (Crivellari et al. 2003).

4. Preliminary results

The space available allows us to present only what we consider a striking example of the capabilities offered by our numerical laboratory for modelling stellar atmospheres.

Thanks to the IIM we are now in a position to compute models that range from very deep inner layers up to outermost layers of arbitrarily small ($\tau_{Ross} \ll 10^{-12}$) optical depth. That cannot be achieved by means of the other numerical methods corrently in use, which are limited by the number of layers that can be considered in the computation.

Many years since it was pointed out (Morossi et al. 1993) that, in contrast with the very good agreement shown in the optical and infrared, synthetic spectra of cool stars computed by means of Kurucz's models presented severe discrepancies in the ultraviolet. Only by computing *ad hoc* semi-empirical models, Morossi and co-workers were able to reproduce the observed spectral distribution in the spectral range 1000 – 2000 Å. We understand that the photons in the above spectral range are created in the outermost layers ($\tau_{Ross} < 10^{-6}$), which can hardly be taken into account by classical models. Our models on the contrary, for their capability of handling very many layers, can account for the phenomenology addressed to by Morossi and co-workers.

In order to prove our claim, we considered the case of a solar model, as representative of cool stars. We have firstly computed a solar atmosphere model covering a wide range of optical depths, and have sucessively evaluated its emergeny flux, sampled at the same frequencies employed for the computation of the model.

The results for the range 1000 – 3000 Å are presented in Fig. 1. It clearly shows up that our emergent flux is systematic higher than Kurucz's for $\lambda < 2000$ Å. At 1000 Å, the breach is almost three orders of magnitude.

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