Lecture notes on stellar atmospheres

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Foreword

This document contains lecture notes on the course MNFFY X1/H98 "Stjerneatmosfærer" (Stellar atmospheres) read in the fall semester 1998 at the Physics Institute of NTNU, Trondheim. The course follows the classical text-book "Stellar atmospheres" by D. Mihalas, [3]. Only comments and additions to chapters (listed according to the 2nd edition) included into the program of the course will be explicitly written in the present document. Some more topics connected mainly with the observational practice (spectroscopy and photometry) and with the cases of extended atmospheres and atmospheres of binaries are added by the lecturer. The course could be continued on a summer practice at Ondřejov observatory close to Prague (at the 2-m spectroscopic telescope) and there are different possibilities for master or PhD. thesis in both theoretical as well as observational branch of the field.

The Chapter 5 has been added for the purpose of the course SIF4086 "Stjernefysikk" (Physics of stars) read in the fall semester 2000 following the text-book "The physics of stars" by A.C. Phillips, [5].

Chapter 1

Introduction

1.1 Goals of the stellar-atmosphere studies

Theory of stellar atmospheres is important for manifold reasons. First, by their definition, stellar atmospheres are the surface layers of stars where the observable spectrum is formed. The detailed understanding of the physical processes influencing the formation of outgoing light in this region is thus crucial for its quantitative analysis and gaining an information from the observations. This facilitates our knowledge of basic stellar parameters and the inner structure of stars. In this way, the theory of stellar atmospheres contributes to the progress of many other branches of astrophysics up to cosmology.

Another importance of the subject in question consists in its physical background. The basic feature of stellar atmospheres is their thermodynamic non-equilibrium which is dominated by the strong anisotropic radiation field. Stellar atmospheres can thus be used as laboratories of plasma physics, in which the atomic parameters (probabilities of quantum transitions) can be tested.

Also the mathematical methods developed in stellar atmospheres can be widely used in many other problems.

1.2 Basic concepts

Taking the atmosphere of the Sun as the best known example, we find its thickness of the order of several hundreds of km (cf. [3, chap. 7-7]), which is well negligible in comparison with the solar radius. This explains why we can see the sharp edge of the limb of solar disk and also why in the standard models we mostly approximate stellar atmospheres by planeparallel slabs. From the H-R diagram we can estimate the range of effective temperatures ($\sim 3 \times 10^3 - 5 \times 10^4$K) and gravity accelerations ($\sim 10^4 - 10^5$g/cm^2 for main sequence stars and $\sim 1 - 3 \times 10^3$g/cm^2 for supergiants), which are the main characteristic parameters of any atmosphere. It follows from here, that for hot supergiants the thickness of their atmospheres is not negligible and spherical models give better approximation. The solar observations do not in fact justify the second part of the standard assumption, i.e., the homogeneity in the plains of symmetry of stellar atmospheres. Spots with different effective temperatures (and sometimes also chemical composition and magnetic field) are observed in even larger extend in some other stars. Homogeneity of atmospheres is violated also by gravity darkening in rotating stars or binary components. These effects are usually neglected or, in the better case, modelled by a mosaic composed of locally homogeneous models with varying parameters. There are also other effects mostly ignored in the standard planeparallel model, like the anisotropy caused by either the magnetic field or by the motion of the plasma due to the stellar wind or some oscillations.

Taking into account the typical mass of stellar atmospheres, which is of the order of g/cm^2 and consequently it is even more negligible with respect to the rest of star than its volume, the problem of modelling the atmospheres may seem to be childish compared to the models of stellar interiors. This impression may be strengthened by the facts that the energy radiated by stars is released by thermonuclear reactions in stellar interiors, while in the atmospheres it is only reradiated, and that the interiors are modelled in sequences of the time evolution, while for the atmospheres is calculated their instantaneous picture only. However, the fact of thermodynamic non-equilibrium mentioned in the previous Section makes the physics and especially the numerical modelling of atmospheres more complicated. For modelling of the instantaneous radial structure of stellar interiors we solve a set of ordinary differential equations and the evolution in the time-coordinate is simply integrated as causal consequence of the last previous model. However, for the model atmosphere (even with the above mentioned simplifying assumptions) we need to solve a set (in frequencies) of two-dimensional integro-differential equations for the intensity of light as a function of depth and angle. These equations are mutually coupled with other equations of the structure of atmosphere.

The thermodynamic non-equilibrium of the radiation in stellar atmospheres can be in fact verified by the simple observation with naked eye – the fact that we can see stars shining on the background of the sky implies the existence of macroscopic flows, which should disappear in an exact equilibrium. While the same radiative energy flow in the interiors is only a small perturbation of the very dense radiation field, in the atmospheres we meet at one point outflowing radiation with distribution corresponding approximately to the effective temperature of the star and almost no radiation in the opposite direction. There is thus great discrepancy between the colour temperature of the radiation and the temperature which corresponds to the mean (in all directions) of the density of light. Different radiative processes in the plasma which tend to establish thermodynamic equilibrium between the inner degrees of freedom (kinetic, ionization or excitation energy levels) and the radiation thus pull the relative temperatures[1] of different couples of states to different values. This source of non-equilibrium is partly compensated by non-radiative (collisional) transitions which tend to establish the equilibrium of the inner states. The competition of these two processes leads to a statistical equilibrium, which is close to thermodynamic equilibrium between states for which the collisions prevail, while for states strongly interacting with the radiation there can be significant deviations from the equilibrium distribution (corresponding to the temperature of other states).

[1] Let us remind that the temperature can be exactly defined only for states which are at thermodynamic equilibrium, i.e., which obey an equilibrium distribution law (e.g., Boltzmann distribution for classical particles or Bose-Einstein or Fermi-Dirac for quantum particles) with the corresponding temperature. For two energy levels we can find a temperature describing the ratio of their population. This temperature may be even negative, which facilitates a laser effect.