ATMOSPHERES OF EARLY TYPE STARS

Specification

The topic *Atmospheres of early-type stars* has two individual ingredients, a (stellar) *Atmosphere*, and an *Early-type star*. We shall specify these two terms in turn.

An *atmosphere* of a star is generally any material connected physically to a star from which the photons escape to the surrounding space. In other words, it is a region where the radiation, observable by a distant observer, originates. Traditionally, the term atmosphere has been understood in a limited sense as a thin layer on the surface of a star. However, the more modern view is that the atmosphere encompasses a region extending far from the star. For instance, the solar corona, which extends even beyond the Earth orbit, is understood as a part of the solar atmosphere; from this point of view we all live in a stellar atmosphere.

The term *early type stars* is somewhat loose. Although this class could be meant to comprise all stars that are indeed in the early stages of their evolution, the typical use of this term specifies early type stars as *massive hot stars*, not necessarily young. Using the common stellar classification, the early type stars typically include stellar classes O, B, and early A, but also more evolved stars like luminous blues variables (LBV), and Wolf-Rayet (WR) stars.

The fundamental parameters of a star are mass (M), effective temperature ($T_{\rm eff}$), and total luminosity (L). Effective temperature quantifies the total radiation flux emergent from a surface; precisely, it is the temperature that a black body would have if it was radiating the same total energy flux as the unit area of the actual stellar surface. Typical values of these parameters are $M \approx 8$ - 100 (or more) times the mass of the Sun ($M_\odot$), $T_{\rm eff} \approx 10{,}000$ - 50,000 K, and $L \approx 10^3$ - 10^6 times the solar luminosity ($L_\odot$).

One of their most significant properties is a strong outflow of matter from their surfaces, reaching velocities of to several thousands km/s, i.e., of the order of 1% of the speed of light. This outflow is called *stellar wind*, and is reviewed in a separate article. Typical values of the mass loss rate from early type stars are $\dot{M} \approx 10^{-9}$ - 10^{-5} solar masses per year, although in extreme cases of LBV and WR stars the mass loss rate may reach up to $\dot{M} \approx 10^{-3}\ M_\odot$/yr. The wind has a profound significance. First, it changes significantly the path of stellar evolution, because the star may actually lose a large part of its initial mass. Second, the mass loss from young, massive stars significantly enriches the interstellar medium by helium and light metals (the enrichment of heavier elements comes from supernova explosions).

In the global astrophysical context, the early type stars have special significance. They physically influence a large space around them. Most importantly, they produce a large portion of ionizing photons for their host galaxy and surrounding intergalactic space (the only competing objects are quasars, which in some cases may provide the bulk of ionizing radiation). As pointed out above, they enrich the interstellar space by He and light metals because of their wind. From the diagnostic point of view, they also have special significance. They are very bright, and therefore may be studied spectroscopically as individual objects in distant galaxies. Reliable model atmospheres for these stars may therefore yield invaluable independent information about distant galaxies, like chemical composition, and, possibly, reliable distances.

Basic Physics of Stellar Atmospheres

There is a separate article on Stellar Atmospheres, where this term is explained in substantial detail and generality. Here we present a brief summary of the stellar atmospheres theory to the extent that is relevant to stress particular features of early-type atmospheres.

From the physical point of view, a stellar atmosphere is generally a plasma composed of many kinds of particles, namely atoms, ions, free electrons, molecules, or even dust grains. In an early-type stellar atmosphere, because of the high temperature and strong radiation field, there are typically no molecules nor dust grains present, at least in the layers that are traditionally considered as an atmosphere. Nevertheless, molecules and dust may still be present in the very remote parts of an atmosphere.

The total particle density ranges from, say, 10^6 to 10^{16} cm^{-3}. It can be shown that under these densities the elastic collisions between particles are frequent enough to yield very nearly a Maxwellian velocity distribution for all particles; moreover with the same associated kinetic temperature. We refer to it as *electron temperature*, or simply *temperature*. It should be stressed that this temperature is shared only by massive particles; massless particles, like photons, do not generally possess an equilibrium distribution and thus a corresponding temperature. This point will be discussed in detail later on.

What makes atmospheres of early-type stars so special is the fact that because of the strong and energetic radiation field generated in their interiors, the radiation in their atmospheres is not merely a passive *probe* of the physical state of the atmosphere, but rather an important *energy balance agent.* In other words, radiation in fact *determines* the structure of the medium, yet the medium is probed *only* by this radiation. Another important feature is that photons have, under the conditions met in the early-type stellar atmospheres, a much larger mean-free-path than massive particles. This means that radiation is able to transport information to large distances; in other words, radiation *couples* the physical states of rather distant regions of the atmosphere.

The other critical feature that follows from the presence of radiation-induced processes is that the medium is prone to departures from thermodynamic equilibrium. Indeed, the simple fact that we do *see* a star means that photons must *escape* from the atmosphere (in fact, this is a very definition of an atmosphere). Hence the photons must be missing in the atmosphere, and thus some elementary atomic transition processes can no longer be balanced, which leads to a non-equilibrium situation. We shall expand upon this point later in this article. Because of this feature, atmospheres of early-type stars have played, and continue to play, an important role not only in the stellar atmosphere theory, but in overall astrophysical radiative transfer theory in general. The whole non-LTE theory (see later on) was first developed and tested on early-type stellar atmospheres. Consequently, modeling early-type stellar atmospheres is a mature field, which may serve as a methodological guide to other astrophysical objects where the radiation also plays an important role, as, for instance, accretion disks in Active Galactic Nuclei (AGN) and in Cataclysmic Variables (CV), HII regions, and others.

Atmospheric layers

Traditionally, an atmosphere of an early type star is divided into two basic regions, schematically displayed in Figure 1, the photosphere and the stellar wind.

The *photosphere* is the innermost part of the atmosphere. The mass outflow velocities are typically very small there, smaller than the local sound speed, so that they can be neglected. The photosphere is thus assumed to be an essentially *static* region; one of the basic structural equations is thus the hydrostatic equilibrium equation. The radial extent of the photosphere is typically very small compared to the stellar radius, even for hot massive stars.

The stellar photosphere is characterized by the condition of hydrostatic and radiative equilib-

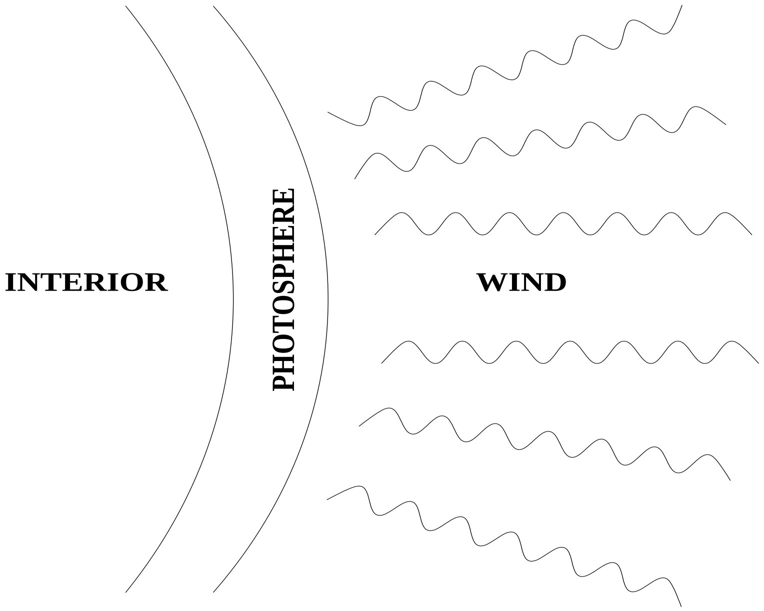

Figure 1: A sketch of basic stellar atmospheric layers. The stellar photosphere is not shown in scale; it would be much thinner.

rium. The hydrostatic equilibrium stipulates that the gradient of the total pressure is balanced by the local gravity acceleration. Because the radial extent of the photosphere is small compared to the stellar radius, the gravity acceleration is essentially constant. The explicit form of this equation is (for a spherically-symmetric star):

$$\frac{dP}{dR} = -\rho G M_* / R^2 \approx -\rho G M_* / R_*^2 \equiv -\rho\, g\,, \tag{1}$$

where P is the total pressure, generally composed of three parts (the gas pressure, $P_{\rm gas}$, the radiation pressure, $P_{\rm rad}$, and the turbulent pressure, $P_{\rm turb}$); R is the radial coordinate; M_* and R_* are the stellar mass and radius, respectively; g is the gravity acceleration at the stellar surface; and ρ the mass density.

The radiative equilibrium simply states that the only energy transport mechanism is radiation. In other words, it says that the total radiation energy absorbed in a given elementary volume of material in the photosphere is equal to the total radiation energy emitted in the volume. (As it is customary in astrophysical radiative transfer, a functional dependence on the frequency ν is typographically denoted as a subscript ν standing at the corresponding quantity.)

$$\int_0^\infty (\kappa_\nu J_\nu - \eta_\nu)\, d\nu = 0\,, \tag{2}$$

where κ_ν is the absorption coefficient, η_ν the emission coefficient, and J_ν the mean intensity of radiation. Equation (2) also states that the energy is only *transported* in the photosphere; there is no energy *generated* there. This makes a sharp distinction from the stellar interior (where the energy is generated by nuclear reactions), and from the other atmospheric layers (e.g., stellar chromospheres, coronae, or winds), where the energy is generated by dissipation of various wave motions.

It can be easily shown that the atmospheres of early-type stars are convectively stable; this feature makes a significant difference from the atmospheres of cooler stars (type late A and later), where convection is another significant mechanism of energy transfer. Roughly speaking, the convection is a transport of energy by rising and falling bubbles of material with properties (e.g. temperature) different from the ambient medium.

The *stellar wind* is the region where the outflow velocities are comparable or larger than the local sound speed. The radial extent of this region may be comparable to or, in some cases, significantly larger than, the radius of the stellar photosphere. This region is comprehensively reviewed in a separate article.

In some cases, there may be a third, more remote layer, which may contain molecules and dust. For instance, very young stars may still be enveloped by their placental matter. These regions are probed by the infrared and radio radiation (see also articles on Star Formation, Molecular Clouds, etc.).

Microscopic processes

From the very nature of stellar atmospheres it is clear that the detailed description of the processes of interaction between radiation and matter is a crucial ingredient of the stellar atmospheres theory. These processes determine (i) how the radiation is transported in the atmosphere, and (ii) what is the distribution of the microscopic degrees of freedom of the massive particles (e.g., the excitation and ionization state of the individual atomic species, etc.).

The interaction between radiation and matter is described phenomenologically through the radiative transfer equation:

$$\left(\frac{1}{c}\frac{\partial}{\partial t} + \mathbf{n}\cdot\nabla\right) I(\nu,\mathbf{r},\mathbf{n},t) = \eta(\nu,\mathbf{r},\mathbf{n},t) - \chi(\nu,\mathbf{r},\mathbf{n},t)\, I(\nu,\mathbf{r},\mathbf{n},t)\,. \tag{3}$$

Here, I is the *specific intensity* of radiation, defined such that it is the energy transported by radiation in a unit frequency range at the frequency ν, across a unit area perpendicular to the direction of propagation, $\mathbf{n}$, into a unit solid angle, and in a unit time interval. The specific intensity provides a complete description of the unpolarized radiation field from the macroscopic point of view. (This description can be generalized to an arbitrarily polarized light by introducing the *Stokes vector* instead of the scalar intensity, but we will not consider this concept in this article, and assume an unpolarized radiation, which is quite appropriate in the context of early-type stars).

Quantities χ and η are phenomenologically defined as *absorption* and *emission* coefficients, respectively. They are defined analogously to the specific intensity, namely as the energy removed or added to a beam of radiation at unit frequency range, solid angle, area, and time.

It is known from the quantum theory of radiation that there are three types of elementary processes that give rise to an absorption or emission of a photon: 1) induced absorption – an absorption of a photon accompanied by a transition of an atom/ion to a higher energy state; 2) spontaneous emission – an emission of a photon accompanied by a spontaneous transition of an atom/ion to a lower energy state; and 3) stimulated emission – an interaction of an atom/ion with a photon accompanied by an emission of another photon with identical properties. In the astrophysical formalism, the stimulated emission is usually treated as negative absorption.

In thermodynamic equilibrium, the microscopic detailed balance holds, and therefore the radiation energy absorbed in an elementary volume in an elementary frequency interval is exactly balanced by the energy emitted in the same volume and in the same frequency range, i.e., $\chi I = \eta$. Moreover, in thermodynamic equilibrium, the radiation intensity is equal to the Planck function, $I = B$, where

$$B(\nu, T) = \frac{2h\nu^3}{c^2} \frac{1}{\exp(h\nu/kT) - 1} \,. \tag{4}$$

We are then left with an interesting relation that in thermodynamic equilibrium, $\eta/\chi = B$, which is called *Kirchhoff's law.*

The absorption and emission coefficients are written explicitly as

$$\chi_\nu = \sum_i \sum_{j>i} \left[n_i - (g_i/g_j) n_j\right] \sigma_{ij}(\nu) + \sum_i \left(n_i - n_i^* e^{-h\nu/kT}\right) \sigma_{i\kappa}(\nu) + \sum_\kappa n_{\rm e} n_\kappa \sigma_{\kappa\kappa}(\nu, T) \left(1 - e^{-h\nu/kT}\right) + n_{\rm e}\sigma_{\rm e} \ , \tag{5}$$

where the four terms represent, respectively, the contributions of bound-bound transitions (i.e. spectral lines), bound-free transitions (continua), free-free absorption (also called brehmstrahlung), and of electron scattering. In the stellar atmospheric conditions the electron scattering is to a good approximation coherent (i.e., without a change of photon frequency – Thomson scattering). A more general case, with a decrease or increase of the photon energy (frequency), is called Compton, or inverse Compton scattering, respectively. Typically, the effects of Compton scattering are negligible in the atmospheres of early-type stars (they may be important in the atmospheres of very hot subdwarfs, white dwarfs, and pre-white-dwarfs). In principle, other scattering terms, like for instance Rayleigh scattering, may also be added if needed.

Here, n_i is the occupation number (population) of an atom in the energy level labeled i, g_i the corresponding statistical weight, and n_i^* denotes an equilibrium population of level i corresponding to temperature T, and electron density $n_{\rm e}$. $\sigma(\nu)$ are the corresponding cross-sections; subscript κ denotes the "continuum," and n_κ the ion number density. The negative contributions in the first three terms represent the stimulated emission. There is no stimulated emission correction for the scattering term, because this contribution exactly cancels with ordinary absorption. The relation between the bound-bound cross section $\sigma_{ij}(\nu)$ and the well-known Einstein coefficients for the for the photo-excitation is $\sigma_{ij}(\nu) = (h\nu_0/4\pi) B_{ij}\phi(\nu)$; $\phi(\nu)$ is the so-called *absorption profile coefficient*, normalized to unity, $\int \phi(\nu)\, d\nu = 1$. It represents the conditional probability density that if a photon is absorbed in the transition $i \rightarrow j$, it is absorbed in the frequency range $(\nu, \nu + d\nu)$.

Analogously, the thermal emission coefficient is given by

$$\eta_\nu = \frac{2h\nu^3}{c^2} \left[\sum_i \sum_{j>i} n_j (g_i/g_j) \sigma_{ij}(\nu) + \sum_i n_i^* \sigma_{i\kappa}(\nu) e^{-h\nu/kT} + \sum_\kappa n_{\rm e} n_\kappa \sigma_{\kappa\kappa}(\nu, T) e^{-h\nu/kT} \right] \,. \tag{6}$$

The three terms again describe the bound-bound, bound-free, and free-free emission processes, respectively.

The absorption and emission coefficients are thus described through the corresponding cross sections—given by the atomic physics, the local thermodynamic parameters, T, and $n_{\rm e}$, and the atomic level populations for all the levels involved in the microscopic processes that give rise to an absorption and emission at frequency ν; such a number may be enormous. The chief difficulty of the stellar atmospheres theory is that the level populations generally depend on other state parameters and the radiation field.

LTE versus non-LTE

It is well known from statistical physics that a description of material properties is greatly simplified if the thermodynamic equilibrium (TE) holds. In this state, the particle velocity distributions as well as the distributions of atoms over excitation and ionization states are specified uniquely by two thermodynamic variables. In the stellar atmospheres context, these variables are usually chosen to be the (kinetic) temperature (T), and the total particle number density (N), or the electron number density ($n_{\rm e}$). From the very nature of a stellar atmosphere it is clear that it cannot be in thermodynamic equilibrium – we *see* a star, therefore we know that photons must be escaping. Because photons carry significant momentum and energy, the elementary fact of photon escape has to give rise to significant *gradients* of the state parameters in the stellar outer layers.

However, even if the assumption of TE cannot be applied to a stellar atmosphere, we may still use the concept of *local thermodynamic equilibrium* – LTE. This assumption asserts that we may employ the standard thermodynamic relations not globally for the whole atmosphere, but *locally*, for local values of $T(\mathbf{r})$ and $N(\mathbf{r})$ or $n_{\rm e}(\mathbf{r})$, despite the gradients that exist in the atmosphere. This assumption simplifies the problem enormously, for it implies that all the particle distribution functions may be evaluated locally, without reference to the physical ensemble in which the given material is found. Notice that the equilibrium values of distribution functions are assigned to *massive particles*; the radiation field is allowed to depart from its equilibrium, Planckian, distribution function (i.e., $I = B$ is valid only in strict TE).

Specifically, LTE is characterized by the following three distributions:

- Maxwellian velocity distribution of particles
- Boltzmann excitation equation,
- Saha ionization equation.

Microscopically, LTE holds if all atomic processes are in *detailed balance.* i.e. if the number of processes $A \rightarrow B$ is exactly balanced by the number of inverse processes $B \rightarrow A$. By A and B we mean any particle states between which there exists a physically reasonable transition. For instance, A is an atom in an excited state, and B the same atom in another state (either of the same ion, in which case the process is an excitation/de-excitation; or of the higher or lower ion, in which case the term is an ionization/recombination).

In contrast, by the term non-LTE (or NLTE) we mean any state that departs from LTE. In practice, one usually means that populations of some selected energy levels of some selected atoms/ions are allowed to depart from their LTE value, while the velocity distributions of all particles are assumed to be Maxwellian, all at the same local kinetic temperature, T.

One of the big issues of modern stellar atmospheres theory is whether, and if so to what extent, departures from LTE should be included in numerical modeling. Generally, to understand why and where we may expect departures from LTE, let us turn to the microscopic definition of LTE. It is clear that LTE breaks down if the detailed balance in at least one transition $A \rightarrow B$ breaks down. We distinguish the *collisional transitions* (arising due to interactions between two or more massive particles), and *radiative transitions* (interactions involving particles and photons). Under stellar atmospheric conditions, collisions between massive particles tend to maintain the local equilibrium (because velocities are Maxwellian). Therefore, the validity of LTE hinges on whether the radiative transitions are in detailed balance or not.

Again, the fact that the radiation escapes from a star implies that LTE should eventually break down at a certain point in the atmosphere. Essentially, this is because detailed balance in radiative transitions generally breaks down at a certain point near the surface. Because photons escape (and more so from the uppermost layers), there must be a lack of them there. Consequently, the number of photoexcitations (or any atomic transition induced by absorbing a photon) is less than a number of inverse processes, spontaneous de-excitations (we neglect here, for simplicity, stimulated emission).

These considerations explain that we may expect departures from LTE if the following two conditions are met: i) radiative rates in some important atomic transition dominate over the collisional rates; and ii) radiation is not in equilibrium, i.e. the intensity does not have the Planckian distribution. Because the collisional rates are proportional to the particle density, the departures from LTE tend to be small for high densities. Likewise, deep in the atmosphere, photons do not escape, and so the intensity is close to the equilibrium value. Departures from LTE are therefore small, even if the radiative rates dominate over the collisional rates. On the other hand, departures from LTE are important for low-density media immersed in a strong radiation field, which are precisely the conditions met in the atmospheres of early-type stars.

Model Atmospheres

By the term *model stellar atmosphere* we mean a specification of all the atmospheric state parameters as functions of position. These parameters are obtained by solving appropriate structural equations, which, in the case of stellar photospheric models, are the equations of hydrostatic equilibrium, radiative equilibrium, radiative transfer equation, and the set of statistical equations (rate equations) for the atomic level populations. In the case of LTE models, the rate equations are not needed because the level populations are given by the Saha-Boltzmann distribution. Because the problem is very complex, it is impossible to find analytical solutions. Therefore, we have to resort to numerical simulations. In order to make the overall problem tractable, one has to make a number of simplifications by invoking various approximations. The quality of an appropriate model, and consequently its applicability to the individual stellar types, is closely related to the degree of approximation used in the construction of the model. Needless to say, the degree of approximation critically influences the amount of computational effort to compute it. It is fair to say that the very art of computing model stellar atmospheres is to find such physical approximations that allow the model to be computed with a reasonable amount of numerical work, yet the model is sufficiently realistic to allow its use for a reliable interpretation of observed stellar data. The adopted approximations are therefore critical. There are several types of approximations that are typically made in the model construction; we shall describe most important types in turn.

Approximations of the geometry

By the geometrical simplification we mean that either some prescribed geometrical configuration is assumed, or some special kind of overall symmetry is invoked. The goal of those simplifications is to reduce the dimensionality of the problem from a spatially 3-dimensional problem to 1- or 2-D problem. The most popular approximations are (from simplest to more complex):

– Plane-parallel geometry, with an assumption of horizontally homogeneous layers. This decreases the number of dimensions to one: the depth in the atmosphere. This approximation is typically quite reasonable for stellar photospheres, which indeed are by several orders of magnitude thinner than the stellar radius, so the curvature effects are negligible. The assumption of horizontal homogeneity is made for the sake of simplicity - there is no plausible verification of this approximation, and, moreover, observational evidence mostly shows that stellar surfaces are far from being homogeneous (a notorious example being detailed pictures of the solar surface). Nevertheless, even in the presence of inhomogeneities, 1-D models still have their value since in many cases one may construct different 1-D models for the individual "patches" on the surface.

– Spherical symmetry. Again, the problem is one-dimensional. The approach is used for extended atmospheres, for which the atmospheric thickness in no longer negligible with respect to the stellar radius. Typically, we have to consider such models for early-type giants and supergiants, as well as for earliest types of main-sequence O stars.

– Multi-dimensional geometry. This field is at its infancy. A numerical solution is extremely demanding on computer time and memory, and only very recently has the computer power reached a stage that calculating such models is becoming feasible. Some detailed model atmospheres including 2-D and 3-D geometry have been constructed for a Solar atmosphere, and some 2-D simulations of early-type stellar winds have been performed (see the article on Stellar Winds).

Approximations of the dynamical state of the atmosphere

This is basically a specification of the realism of the treatment of the macroscopic velocity fields. From the simplest to the most complex the approaches are the following:

– Static models, in which the macroscopic velocity field is set to zero. As discussed above, these models describe a *stellar photosphere.*

– Models with an *a priori* given velocity field. In these models the velocities are taken into account explicitly, and their influence upon other state parameters, in particular the emergent radiation, is studied in detail. In these models, one can either consider only a dynamical region (i.e., the wind) and take an incoming radiation from the photosphere as given a priori – the so-called core-halo model; or a model which treats the photosphere and the wind on the same footing. Such models are called *unified models.*

– Models where the velocity field is determined self-consistently by solving the appropriate hydrodynamical equations. This problem is very complicated because the wind driving force is given by the absorption of photons in thousands to millions of metal lines (the so-called line-driven wind – see the article on Stellar Winds), so the hydrodynamical equations should be solved together with at least an approximate treatment of radiative transfer in spectral lines.

Approximations of the opacity sources

In real stellar atmospheres, there is an enormous number of possible opacity sources. It is impractical to take all of them into account in full detail. The light elements (H, He, C, N, O) have comparatively a small number of lines per ion (say 10^2 to 10^4) because of a relatively simple atomic level structure. The number of lines generally increases with increasing atomic number, and for the iron-peak elements (Fe and Ni being the most important ones), we have of the order of 10^6 to 10^7 spectral lines per ion! Therefore, the opacity (and emissivity) may be an enormously complicated function of frequency.

There are several approximations that are to meant to reduce this complexity considerably:

– Models constructed using certain frequency-averaged opacities; these models are called *grey* models. The approach is based on the implicit assumption that the behavior of the frequency-averaged intensity of radiation is well described by means of some frequency-averaged opacities. There are several possible mean opacities, depending on how exactly the averaging is done. The most used averaged opacity is the *Rosseland mean* opacity, defined by

$$\frac{1}{\chi_R} \equiv \frac{\int_0^\infty (1/\chi_\nu)(dB_\nu/dT)d\nu}{\int_0^\infty (dB_\nu/dT)d\nu}\,, \tag{7}$$

where χ_ν is the opacity (per gram of stellar material). Because averaging is done for $1/\chi$, the largest weight is given to regions of lowest opacity, which are the most efficient regions for the energy flux transport. This explains why the Rosseland mean opacity is well suited for describing the total radiation flux.

The grey model atmospheres are no longer used for spectroscopic analysis, but they are useful for providing an initial estimate in any iterative method for constructing more realistic model atmospheres, and they are very useful for pedagogical purposes because they allow one to understand a rough behavior of temperature and radiation field as a function of depth in the atmosphere.

– A possibility is to use stepwise frequency averages for a number of subintervals (frequency bins), called sometimes multi-frequency/multi-grey method. This approach was used in constructing model stellar atmospheres only rarely, but is used in other branches of astrophysical and laboratory radiative transfer.

– A completely different approach is to construct a model atmosphere neglecting the line opacity completely. Although this may seem very crude, such models may actually provide reasonable results for very metal-poor stars because, as was pointed put above, H and He posses only a small number of lines, which occupy only a very small frequency range and therefore have a small influence on the model structure. (Strictly speaking, this is not completely true, because just 3 of the most important hydrogen lines - Lα, Lβ, and Hα may already have an important indirect effect upon the temperature structure in the outer layers of early-type photospheres.) In any event, this approximation was introduced at the early stages of development of the non-LTE model atmospheres, and was motivated by limitations of then available computers and numerical techniques.

– An obvious next level of approximation is to consider a small number of lines (typically tens to hundreds) explicitly, while neglecting the bulk of metal lines; the selected lines are those which presumably have the largest effect upon the atmospheric structure.

– Finally, one can take into account, by one way or another, “all” metal lines. Such models are traditionally called *metal line-blanketed model atmospheres.* The problem of constructing such models is computationally very demanding. Under the assumption of LTE it is, however, considerably simplified because the opacity and emissivity is a function of only local temperature and electron density; the only problem is the complicated frequency dependence of the opacity. Without the approximation of LTE the problem is significantly more difficult because one has to determine all the atomic level populations and temperature self-consistently with the radiation field.

Approximations concerning the thermodynamic equilibria

Here, as we discussed above, the issue is whether the approximation of LTE is adopted or not. If we assume LTE, the resulting model atmospheres are called LTE models. Two state parameters, the temperature, T, and density, ρ (or electron density, n_e), suffice to describe the physical state of the atmosphere at any given position. In practice, LTE models may be useful only for stellar photospheres, because for extended atmospheres and/or stellar winds this approximation breaks down completely and its application would yield erroneous and misleading results.

The models that take some kind of departure from LTE into account are called non-LTE (or NLTE) models. This term is rather ambiguous because it is not a priori clear what is actually

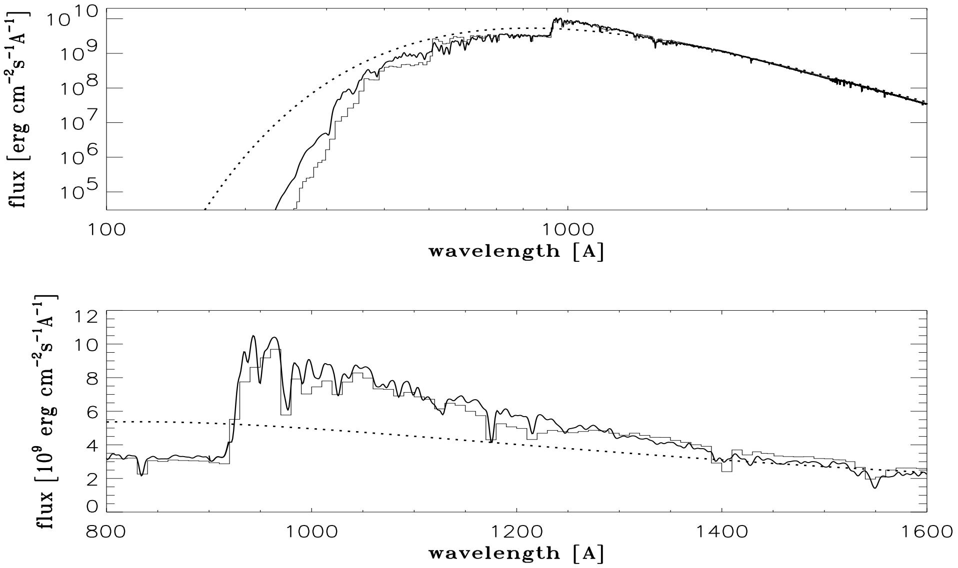

Figure 2: A comparison of the predicted flux from the fully blanketed NLTE model atmosphere with $T_{\rm eff} = 35,000$ K, log $g = 4$ (heavy line); the Kurucz LTE line-blanketed model for the same parameters (thin histogram); and a black-body flux for $T = T_{\rm eff} = 35,000$ K (dotted line). The upper panel dispays the flux in a wide range or wavelengths (notice the logarithmic ordinate), while the lower panel shows the flux (in the linear scale) in the vicinity of the Lyman limit. The flux was convolved with Gaussian broadening with FWHM=5 Å.

allowed to depart from LTE in a given model. In early models, the populations of only few low-lying energy levels of the most abundant species, like H and He, were allowed to depart from LTE; the rest were treated in LTE. During the development of the field, progressively more and more levels were allowed to depart from LTE. The situation is similar for stellar photospheres (static models), as well as for stellar winds and for unified models.

Existing model atmospheres

Because the stellar winds are covered in an independent article, we concentrate here on static models, i.e., models of early-type stellar photospheres.

The most extensive grid of LTE line-blanketed models is that of Kurucz; the grid covers effective temperatures between 3500 K and 50,000 K, so that it includes stars much cooler than early-type stars.

During the last three decades, it was amply demonstrated that departures from LTE are crucial for spectroscopic studies of early-type stars, even the photospheric layers. Early non-LTE models were constructed already in the late 1960's and in the first half of the 1970's by Mihalas and coworkers. Nevertheless, the numerical problems and sheer amount of computer time and memory needed for computing non-LTE metal line-blanketed model atmospheres have precluded computing such models until the late 1980's. Thanks to the development of a very efficient numerical method for solving the radiative transfer equation simultaneously with other state equations, called the Accelerated Lambda Iteration (ALI) method (see a separate article on Radiative Transfer), this last

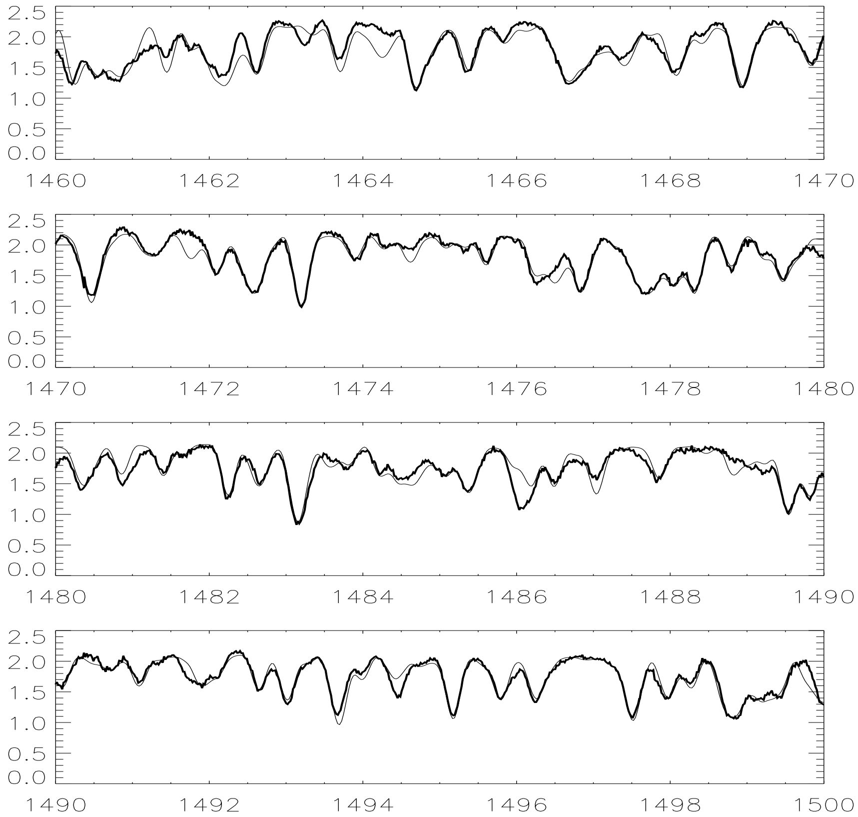

Figure 3: A comparison of the observed HST/GHRS flux for 10 Lac (heavy line) and the predicted flux from the fully blanketed NLTE model atmosphere with $T_{\rm eff} = 35,000$ K, $\log g = 4$, and $v \sin i = 25$ km/s, and for the solar abundances of all species. The predicted flux is convolved with instrumental broadening with FWHM = 0.06 Å. The abscissa is the wavelength in Å, and the ordinate is the flux in 10^{-9} erg cm^{-2} s^{-1} Å^{-1}. Most spectral features are lines of Fe IV, Fe V, Ni IV, and Ni V.

barrier of the classical stellar atmosphere problem was broken, and non-LTE metal line-blanketed model including literally millions of spectral lines in non-LTE are now being constructed. Because sufficiently efficient computer codes for mass production of non-LTE line-blanketed models were being developed only during mid 1990's, there is no comprehensive grid of non-LTE line blanketed models, which would cover the same range of parameters as the Kurucz grid, currently available, but they will very likely be built in the forthcoming years.

From the practical point of view, the most important result of model atmospheres is the prediction of emergent radiation, which is then compared to the observed spectrum in order to deduce basic stellar parameters. Also, theoretical predictions are indispensable for estimating the radiation in unobservable spectrum regions, in particular in the hydrogen Lyman continuum (wavelength less than 912 Å), which produces ionizing photons, but which cannot be directly detected for early-type stars because of the absorption by interstellar hydrogen. (Only two early-type stars, ϵ and β CMa, which are relatively close, and which lie in the direction of a "tunnel" of low density in the local interstellar medium, have detectable Lyman continuum flux as observed by the *EUVE* satellite.)

Figure 2 presents a comparison of predicted flux for a star with $T_{\rm eff} = 35,000$ K, log $g = 4$, which corresponds to a main-sequence late-O type star. The difference between the LTE and non-LTE predictions is important, particularly in the extreme-UV region. For completeness, a black-body flux for $T = T_{\rm eff}$ is also displayed. The black-body flux is obviously no longer used for any analysis of spectra of early-type stars, but is still sometimes being used in other branches of astrophysics, like cosmology, for estimating the total number of ionizing photons produced by young, massive stars. As this figure shows, such estimates may be wrong by several orders of magnitude.

As an example of a detailed predicted spectrum from a most modern, non-LTE metal line-blanketed model atmosphere, we present in Figure 3 a sample of the predicted flux for a non-LTE model for $T_{\rm eff} = 35,000$ K, log $g = 4$, and a high-resolution, high signal-to-noise observation of a late-O main-sequence star 10 Lac secured by the *Goddard High Resolution Spectrograph* (GHRS) aboard the *Hubble Space Telescope* (HST). The agreement between observations and predictions is excellent, and demonstrates a power of the present-day model atmospheres of early-type stars.

Model stellar atmospheres are basic tools to analyze observed stellar spectra. By fitting the observed spectrum by a grid of theoretically predicted spectra one can derive the basic parameters used for constructing the models, i.e., the effective temperature, surface gravity, chemical composition, and, in the general case, the mass loss rate. From those parameters, one can derive the fundamental stellar parameters, like the mass, radius, and luminosity. Besides these, there are a number of secondary parameters, such as the rotational velocity, or auxiliary parameters describing the nature of atmospheric velocity fields, etc. Detailed techniques for determining those parameters are described in separate articles (Chemical Compositions; Stellar Distances; Stellar Luminosities; Stellar Masses; Stellar Spectra). Here we just mention that thanks to modern, sophisticated model atmospheres, a typical accuracy of determining the effective temperature of early-type stars is about 5 %, the accuracy in $\log g$ about 0.1 - 0.2 dex, and the accuracy of chemical abundances about 0.2 - 0.3 dex.

Bibliography

The fundamental textbook of the field is

Mihalas, D. (1978): *Stellar Atmospheres*, 2nd ed., Freeman, San Francisco

A good textbook that covers both the theoretical and observational aspects of the stellar atmospheres is

Gray, D.F. (1992): *Observations and Analysis of Stellar Photospheres*, 2nd ed., Cambridge Univ. Press, Cambridge

Other related textbooks on physical aspects of radiative transfer include

Rybicki, G.B., Lightman, A.P. (1979): *Radiative Processes in Astrophysics*, Wiley-Interscience, New York

Shu, F.H. (1991): *The Physics of Astrophysics I. Radiation*, University Science Books, Mill Valley

and an elementary-level textbook is

Böhm-Vitense, E. (1989): *Introduction to Stellar Astrophysics II. Stellar Atmospheres*, Cambridge Univ. Press, Cambridge

There are two books which present a collection of reviews on various mathematical and numerical aspects of radiative transfer

Kalkofen, W. (Ed.) (1984): *Methods in Radiative Transfer*, Cambridge Univ. Press, Cambridge

Kalkofen, W. (Ed.) (1987): *Numerical Radiative Transfer*, Cambridge Univ. Press, Cambridge

An excellent review paper of properties of early-type stars is

Kudritzki, R. P., Hummer D. G. (1990): *Ann. Rev. Astron. Astrophys.* **28**, 303

A grid of LTE model atmospheres is described in

Kurucz, R. L. (1979): ApJS **40**, 1

and some recent non-LTE line-blanketed model atmospheres in

Dreizler, S., Werner, K. (1993): A&A, **278**, 199.
Hubeny, I., Lanz, T. (1995): ApJ **439**, 875
Aufdenberg, J. P., Hauschildt, P. H., Shore, S. N., Baron, E.: (1998) ApJ **498**, 837

And, finally, there are several conference proceedings which contain many excellent review papers on the stellar atmospheres theory, e.g.

Crivellari, L., Hubeny, I., Hummer D. G. (Eds.) (1991): *Stellar Atmospheres: Beyond Classical Models*, NATO ASI Series C 152 (Dordrecht: Kluwer)
Heber, U., Jeffery, C.J. (Eds.) (1992): *The Atmospheres of Early-Type Stars*, Lecture Notes in Phys. 401, Springer, Berlin
Howarth, I.D. (Ed.) (1997) *Boulder-Munich II: Properties of Hot Luminous Stars*, PASP Conf. Ser. Vol. 131, Astron. Soc. Pacific, San Francisco

IVAN HUBENY