# *Preface*

The purpose of this book is to provide an account of the major advances achieved in making quantitative spectroscopic analyses of the observable outer layers of stars. These analyses can now be done with a much higher degree of realism thanks to a deeper understanding of the interaction between the material and the radiation field in a stellar atmosphere, more accurate and more complete data from space-based and ground-based observations, markedly improved computational algorithms, and the immense increase in the speed of computers. We omit some topics that today are mainly of historical interest and focus instead on providing a solid physical formulation of the problem and methods by which it can be solved.

We have in mind three groups of readers: (1) astronomers who understand the astrophysical context and want to acquire deeper insight into the subject's physical foundations and/or to learn about modern computational techniques for treating non-equilibrium radiative transfer, (2) physicists who know the underlying physics, but are not familiar with the motivation for this work or how to deal with radiative transfer, and (3) students who need to learn both the reasons for, and the methodology of, this discipline. We try to offer a description of both the physics and mathematics that is adequate to do research in the field, rather than a short summary. Several other good books at a more introductory level are available, e.g., [22, 132, 133, 186, 246, 391, 1003, 1006, 1178].

Strands from many diverse topics must be woven together to form the complete picture. For example, the occupation numbers in the material in the outer *observable* layers of a star are determined by kinetic equations containing the rates of radiative and collisional processes. These layers have very low densities, so collision rates are much smaller than radiative rates; hence the latter essentially determine the state of the material. Therefore, the *material's absorption and emission coefficients are set by the local radiation field*. But, in turn, *the local radiation field is the result of not only local photon emission and absorption, but also photons that have penetrated from other (perhaps remote) points in the atmosphere where the physical conditions may be quite different. In short, the radiation field determines the non-equilibrium properties of the material, but those properties in turn determine the radiation field; the two are inextricably coupled.* This is the central problem in computing a theoretical stellar spectrum.

In this book we have concentrated mostly on hot stars, whose atmospheres are dominated by radiative processes and are reasonably well approximated by homogeneous planar or spherical layers. The situation is more complex for cool stars, in which energy is transported by both radiation and convection. The latter is a time-dependent, quasi-turbulent, three-dimensional flow posing problems only now being addressed with some degree of accuracy. We will refer only to the phenomenological *mixing-length picture* of convective energy transport. We make no attempt to discuss magnetically dominated structures in stellar chromospheres and coronae.

The material presented here enables one to calculate radiative transfer in, and to make a quantitative spectroscopic analysis of, any low-density plasma. It applies in the observable layers of any astrophysical object, not just stars. It also provides necessary background for the study of radiation hydrodynamics, in which radiation can drive a flow of the material.

The book is meant to be reasonably self-contained, but the reader should be familiar with the elements of quantum mechanics and special relativity. Also, we point out that the ordering of its chapters is somewhat unconventional compared to other texts on this subject, so we ask serious students of the subject to use an "iterative" approach in reading it. Readers who re-read earlier parts of the book bearing on material they are currently studying will reap solid rewards in their understanding. We believe that a judicious instructor can use this book as a text for beginners or a monograph for advanced students and research scientists. In broad outline, the topics covered are the following.

## ASTROPHYSICAL BACKGROUND

Chapter 1 contains a brief sketch of the historical development of the study of stellar atmospheres. In its last section we point out specific areas in which this work makes important contributions to other problems in the larger arena of astrophysics. Chapter 2 describes the wide variety of observational data that both underlie and test the theoretical structures we use to interpret them.

## RADIATION

In chapter 3 we present macroscopic, electromagnetic, and quantum mechanical descriptions of a radiation field. These representations are used in all later work. In chapter 4 we use thermodynamics and statistical mechanics to derive the physical properties of matter and radiation in the limit of strict *thermodynamic equilibrium* (TE) and introduce the concept of *local thermodynamic equilibrium* (LTE). Many of the formulae obtained in this chapter are used throughout the remainder the book.

## ABSORPTION AND EMISSION OF RADIATION

The quantum mechanics of *photon absorption and emission* in bound-bound, bound-free, and free-transitions is discussed in chapter 5, and the *scattering of continuum radiation* in both the low-energy and relativistic limits is covered in chapter 6. In chapter 7, we sketch the quantum-mechanical calculation of absorption cross sections for some astrophysically important atomic and molecular opacity sources. In chapter 8 we discuss the broadening of spectral lines in frequency resulting from (a) the finite lifetimes of the atomic levels they connect, (b) Doppler shifts produced by the component of an atom's thermal velocity along the line of sight or of a macroscopic velocity of the material, and (c) semi-classical and quantum mechanical descriptions of the interruptions of the wavetrain by collisions with free electrons and/or other atoms.

## INTERACTIONS BETWEEN RADIATION AND SPECTRAL LINES

The observable effects of non-equilibrium occupation numbers in the material of a stellar atmosphere are more pronounced in spectral lines than in continua and strongly influence the diagnosis of its physical properties. To understand the interplay between kinetic-equilibrium processes and transport processes, we analyze the physics of spectral line formation in a *given* atmospheric structure in the next four chapters.

In chapter 9 we write the kinetic equations that determine the excitation and ionization occupation numbers of material in a general non-equilibrium (NLTE) radiation field. Here we must account for the fact that photons in a spectral line are not scattered coherently, but in general are redistributed over the line profile. In chapter 10 we describe these phenomena in terms of *redistribution functions* obtained from both a semi-classical approach and a rigorous quantum mechanical analysis. It turns out that the semi-classical and quantum results are essentially the same in the limit of weak radiation fields, which is typically the case in stellar atmospheres.

## RADIATION TRANSPORT

In chapter 11 we use the physical information derived in chapters 5–10 to assemble the absorption, emission, and scattering coefficients that appear in the *radiation transport equation*, to give a phenomenological derivation of the transport equation in general coordinates, and to show that it is equivalent to a Boltzmann equation in kinetic theory. We then specialize it to Cartesian, spherical, and cylindrical coordinates, show that its angular moments are dynamical equations for the radiation field, and discuss the closure of the system of moments.

Next we reduce the transport equation to a time-independent *transfer equation*, derive the mathematical operators that connect its moments to the specific intensity of the radiation field, and derive its second-order form, which provides the basis for some of the best computational methods. For physically realistic problems, the solution of the transfer equation cannot be obtained analytically; hence we discretize it (along with constraints discussed in later chapters) to reduce it to a form suitable for numerical computation. Finally, we give a *probabilistic interpretation* of the transfer equation and discuss its very important *asymptotic diffusion limit*.

## NUMERICAL SOLUTION OF THE TRANSFER EQUATION

At this point one has the physical theory necessary to compute the transfer of radiation through a stellar atmosphere. In the next two chapters we review current computational methods for solving the transport equation. As mentioned above, the systems of equations that determine the structure of, and spectrum from, a stellar atmosphere are too complex to be addressed analytically. Therefore, we turn to the ever-increasing power and availability of high-speed digital computers to solve them numerically.

In chapter 12 we describe robust *direct methods*, which can give precise solutions of the transfer problems of interest in this discipline. But to fit observed stellar spectra accurately, it may be necessary to account for the non-equilibrium effects of thousands (or more!) of spectral lines and to compute the radiation field at an immense number of frequencies. Unfortunately, direct methods can be too costly to use in such cases. Therefore, in chapter 13 we describe modern, very effective *iterative methods* that allow us to deal with these daunting problems and to compute more physically realistic model atmospheres.

In chapter 14 we make a first study of non-equilibrium spectral line formation. We start with an analysis of the underlying physics of photon diffusion and destruction in, and escape from, an atmosphere, using a model atom consisting of only *two bound levels and a continuum*. Even though it is extremely oversimplified, we gain very useful physical insight from this problem. We then extend the treatment to the physics of photon transport in *multi-level atoms*. In chapter 15 we discuss spectral line formation when there is *partial redistribution* (i.e., noncoherence) of photons scattered by the line.

## STRUCTURAL EQUATIONS

In chapter 16 we write the equations that determine the *structure* of stellar atmospheres at different levels of physical reality. We start with general equations of hydrodynamics, specialize them to one-dimensional flow, further specialize to one-dimensional steady flow, and then to the structure of *static* atmospheres in planar and spherical geometry. Next we examine briefly *energy transport by convection* in addition to radiation and, finally, the equations that determine the interior structure of stars.

## MODEL ATMOSPHERES

In chapter 17 we describe an efficient method to compute *planar, static, LTE model atmospheres* that satisfy the constraints of *radiative and hydrostatic equilibrium* and account for *line blanketing* by large numbers of spectral lines. The opacity from spectral lines can dominate a star's emergent radiation field and strongly affect its physical structure in its outermost layers. We know today that when one assumes LTE, the results obtained are quantitatively (sometimes even qualitatively) inaccurate. Nevertheless, this problem gives the reader an overview of the issues encountered in constructing models of stellar atmospheres and introduces some of the mathematical techniques used in later work.

Chapter 18 deals with the much more difficult problem of constructing *NLTE model atmospheres*, including line blanketing. The results from such computations yield reliable diagnostic tools to determine the effective temperature, surface gravity, and composition of a wide range of stars. This work has provided valuable insights into the evolutionary histories of stars.

## EXTENDED AND EXPANDING ATMOSPHERES

We describe radiative transport in static *spherically symmetric atmospheres* in chapter 19. This geometry is appropriate for highly evolved stars that have very extended envelopes. The spectra of very hot stars often show evidence of rapid mass loss in *stellar winds* for which spherical symmetry may be a reasonable first approximation. Hence we discuss the solution of the radiative transfer equation for material moving radially outward in a stationary *laboratory frame* (also called the *observer's frame*) in which the material is seen to move and in the *comoving frame*, or *fluid frame*, which moves with the material. In the latter case, the *Sobolev approximation* provides a simple method for solving the transfer problem and predicting the emergent spectrum with modest accuracy.

In chapter 20 we study the dynamics of stellar winds. We first briefly describe thermally driven winds. Next, we concentrate on the dynamics of radiatively driven *stellar winds*, which are observed in very hot stars where the rate of outward momentum input from photons into the material exceeds the binding force of gravity. Here great progress has been made with *global model atmospheres* in which the wind is joined self-consistently to the star's photosphere. The results of this work have importance in many other areas of astrophysics.

## TYPOGRAPHY

We denote physical scalars with *italic* Roman or Greek letters, vectors with **boldface** letters, and tensors and matrices with bold **sans serif** letters. We denote individual components of vectors, tensors, and matrices with italic letters having the appropriate number of subscripts or superscripts. When relativity enters, we use the summation convention for repeated indices. Sections marked with a ★ in the Contents may be omitted on a first reading. As in most technical books, several different physical quantities may be represented by the same symbol because the combined Roman and Greek alphabets do not have enough letters to provide separate characters for each of them.

## REFERENCES AND BIBLIOGRAPHY

The complete bibliography of this book is a valuable asset: it lists both the seminal papers at the historical roots of the subject and the large number of papers resulting from its vigorous pursuit today. It has over 4500 references; were it to be printed, it would occupy more than 300 pages, which is excessive. Therefore, in the text we typically give citations for only the initial paper(s) dealing with a topic or indicate that the citations given are only examples with the construction "see, e.g., [199, 824]";

we have taken advantage of modern technology and put the full list on a web site http://press.princeton.edu/titles/10407.html.

This site holds two files: `biblio.ps` and `biblio.pdf` in standard PostScript and PDF format, respectively, which can be viewed on a monitor or printed. It also contains the BibTex file `biblio.bbl`, from which these files were made; it is in plain-text format and can be read with a screen editor and used to make other bibliographies. Readers can then use authors' names and keywords from the titles of the papers cited to search the biblio.bbl file for other relevant references.

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