Preface

This book is not in any sense complete or exhaustive, and it is not meant to be. Its subject, theoretical astrophysics, is vast and cannot possibly be comprehensively covered in a single volume.

This book has a rather different purpose. It is intended as a textbook for students who have a reasonably complete knowledge of the material usually taught in the introductory courses on theoretical physics: classical mechanics, electrodynamics, quantum mechanics, and thermodynamics. Building upon this assumed foundation, this book adds material typically not covered by the introductory lectures, but required for research work in theoretical astrophysics. It may also be useful as a resource for researchers. Arguably the most important extensions are radiation processes, hydrodynamics, plasma physics and magnetohydrodynamics, and stellar dynamics.

This book provides introductions to these four areas. It is structured into four main chapters and an initial chapter summarising some essential theoretical concepts which the following chapters build upon.

The chapter on radiation processes begins with the Larmor equation from electrodynamics and derives Thomson scattering and a general approach to calculating spectra from it, which is then applied to synchrotron radiation and bremsstrahlung. Up to this point, electromagnetic radiation is described as a classical wave that does not exchange momentum with the charges it originates from or interacts with. The backreaction of radiation on the radiating charge is discussed then before Compton scattering is introduced, and with it the photon picture of electromagnetic radiation. The internal structure of radiating systems such as atoms follows, leading to the calculation of cross sections for the interaction of quantum-mechanical systems with radiation and of the shapes of spectral lines. Finally, radiation is described as an ensemble of photons. Specific intensity, emissivity and opacity, the Planck spectrum and radiation transport are introduced there.

The chapter on hydrodynamics begins with a derivation of the ideal hydrodynamical equations from elementary kinetic theory. It is emphasised that these equations express the (local) conservation of the energy-momentum tensor. This opens the way into relativistic hydrodynamics as well as towards various extensions, such as viscous hydrodynamics and magneto-hydrodynamics. The assumption of an infinitely small mean free path from ideal hydrodynamics is then relaxed, leading to viscous hydrodynamics. Inviscid and viscous flows are considered under certain simplifying conditions. The formation of shocks and the Sedov solution follow before the discussion of several fluid instabilities concludes the chapter. The discussion in this chapter emphasises the root of hydrodynamics in the conservation equation for the energy-momentum tensor, the common origin of non-ideal hydrodynamical effects in particle transport, the importance of integrated statements such as Kelvin's theorem, the Bernoulli equation and the Rankine-Hugoniot conditions, and the general approach to linear perturbation or stability analysis.

The chapter on plasma physics begins with the introduction of the plasma parameters and proceeds to the propagation of electromagnetic waves through a plasma. Dispersion relations are derived generally for transverse and longitudinal waves, touching the phenomenon of Landau damping, and specified for thermal plasmas. The equations of magneto-hydrodynamics are introduced next, emphasising their common ground with hydrodynamics in the vanishing divergence of an energy-momentum tensor. The generation of magnetic fields is briefly discussed, followed by ambipolar diffusion as an example for non-ideal coupling between the plasma charges and the fluid particles. The propagation of electromagnetic waves through cold, magnetised plasmas is studied next, and the chapter concludes with a linear stability analysis, revealing the variety of hydromagnetic and Alfvén modes.

The chapter on stellar dynamics begins with deriving Jeans' equations in parallel to the hydrodynamical equations, emphasising the importance of anisotropic pressure. Stability criteria for stellar-dynamical systems are then derived, leading to the Jeans and Toomre criteria. Finally, the phenomenon of dynamical friction is introduced and discussed, ending with Chandrasekhar's formula for the friction force.

Preparing for this selection of subjects, the initial chapter briefly summarises special relativity and relativistic electrodynamics as well as elementary kinetic theory to lay the foundation for the discussions in the following main chapters.

In all chapters, the attempt was made to trace these four areas of theoretical astrophysics back to their origins in fundamental concepts of theoretical physics. Rather than discussing many examples and trying to cover as many astronomical and astrophysical phenomena as possible, the goal of this book is to reveal the roots of the common approaches in theoretical astrophysics, the choices and assumptions made and the methodical similarities appearing throughout. The book does not aim at explaining the richness of astrophysical phenomena, but at enabling the reader to understand and apply the rich toolbox of theoretical astrophysics by her- or himself. In this spirit, the notorious phrases "one can show" or "as can be shown" do not appear in this book. Every subject discussed is derived from first principles, which is considerably more important to the author than completeness.

This book grew from a one-semester course in theoretical astrophysics developed and regularly taught at the University of Heidelberg. The course comprised four hours of lecture and a two-hour tutorial per week. The amount of material collected here is probably at the upper end of what can be covered in a single term of 15 weeks. If it needs to be pruned, the general idea of the course should not be given up: to reveal the foundations of theoretical astrophysics including its important general assumptions, and to identify the common methodical approaches.

By far the most, if not all of the material summarised and compiled in this book is not new. Its intention lies in the foundation and the arrangement of matters, which may help seeing them from a common and unifying perspective. It is not at all possible to give full reference to the original derivations and presentations, not to mention any specific research results. This is therefore not even attempted. Rather, we give a list of more specialised textbooks and refer to them for further reading on individual subjects.