Astrophysics for Physicists

Designed for teaching astrophysics to physics students at advanced undergraduate or beginning graduate level, this textbook also provides an overview of astrophysics for astrophysics graduate students, before they delve into more specialized volumes.

Assuming background knowledge at the level of a physics major, the textbook develops astrophysics from the basics without requiring any previous study in astronomy or astrophysics. Physical concepts, mathematical derivations and observational data are combined in a balanced way to provide a unified treatment. Topics such as general relativity and plasma physics, which are not usually covered in physics courses but used extensively in astrophysics, are developed from first principles. While the emphasis is on developing the fundamentals thoroughly, recent important discoveries are highlighted at every stage.

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Preface

Particle physics, condensed matter physics and astrophysics are arguably the three major research frontiers of physics at the present time. It is generally thought that a physics student's training is not complete without an elementary knowledge of particle physics and condensed matter physics. Most physics departments around the world offer one-semester comprehensive courses on particle physics and condensed matter physics (sometimes known by its more traditional name 'solid state physics'). All graduate students of physics and very often advanced undergraduate students also are required to take these courses. Very surprisingly, one-semester comprehensive courses on astrophysics at a similar level are not so frequently offered by many physics departments. If a physics department has general relativists on its faculty, often a one-semester course *General Relativity and Cosmology* would be offered, though this would normally not be a compulsory course for all students. It has thus happened that many students get trained for a professional career in physics without a proper knowledge of astrophysics, one of the most active research areas of modern physics.

Of late, many physics departments are waking up to the fact that this is a very undesirable situation. More and more physics departments around the world are now introducing one-semester comprehensive courses on astrophysics at the advanced undergraduate or beginning graduate level, similar to such courses covering particle physics and solid state physics. The physics department of the Indian Institute of Science, where I have worked for more than two decades by now, has been offering a one-semester course on basic astrophysics for a long time. It is a core course for our Integrated PhD Programme in Physical Sciences as well as our Joint Astronomy and Astrophysics Programme. I must have taught this course to more than half a dozen batches.

Over the years, several excellent textbooks suitable for use in one-semester courses on particle physics and solid state physics have been written. The situation with respect to astrophysics is somewhat peculiar. There are several outstanding elementary textbooks on astrophysics meant for students who do not have much background of physics or mathematics beyond what is taught at the high school level. Then there are well-known specialized textbooks dealing with important sub-areas of astrophysics (such as stars, galaxies, interstellar matter or cosmology). However, there have been few attempts at bridging the gap between these two kinds of textbooks by writing books covering the whole of astrophysics at the level of Kittel's *Solid State Physics* or Perkins's *High Energy Physics* – suitable for a one-semester course meant for students who have already studied mechanics, electromagnetic theory, thermal physics, quantum mechanics and mathematical methods at an advanced level. Whenever I had to teach the course *Fundamentals of Astrophysics* in our department, I found that there was no textbook which was suitable for use in the whole course. The present book has grown out of the material I have taught in this course.

While writing this book, I have kept in mind that most of the students using this book will not aspire to a professional career in astrophysics. So I have tried to stress those aspects of astrophysics which are likely to be of interest to a physicist who is not specializing in astrophysics. Astrophysics is an observational science and an acquaintance with the basic phenomenology is absolutely essential for an appreciation of modern astrophysics. While I have introduced the basic phenomenology throughout the book, I believe that a physics student can appreciate astrophysics without knowing what a T Tauri star or what a BL Lac object is. A student who wishes to be a professional astrophysicist and has to master the terminology of the subject (which is sometimes of the nature of historical baggage) can learn it from other books. Rather than covering the details of too many topics, I have tried to develop the central themes of modern astrophysics fully. The trouble with this approach is that no two astrophysicists will completely agree as to what are central themes and what are details! I have used my judgment to develop what I would consider a balanced account of modern astrophysics. There is no doubt that experts in different areas of astrophysics would feel that I have committed the cardinal sin of not covering something in their area of specialization which they regard vitally important. If I succeed in making experts in all different areas of astrophysics *equally* unhappy, then I would conclude that I have written a balanced book! One other principle I have followed is to give more stress on classical well-established topics rather than topics which are still ill-understood or on which our present views are likely to change drastically in future. To give readers a historical perspective, I have sometimes deliberately chosen figures from original classic papers rather than their more contemporary versions, unless the modern figures supersede the original figures in essential and important ways. I have also intentionally kept away from topics which are too speculative or which do not have close links with observational data at the present time, perhaps reflecting my personal taste.

Virtually all branches of basic physics find applications in some topic of astrophysics or other. I have assumed that the readers of this book would have

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sufficient knowledge of classical mechanics, electromagnetic theory, optics, special relativity, thermodynamics, statistical mechanics, quantum mechanics, atomic physics and nuclear physics – something that is expected of an advanced student of physics in any good university anywhere. It is a firm belief of the present author that all physics students at this level ought to know some fluid mechanics and plasma physics. However, keeping in mind that this is not the case for physics students in the majority of universities around the world, a background in fluid mechanics or plasma physics has not been assumed and these subjects have been developed from first principles. General relativity is also developed from first principles without assuming any previous knowledge of the subject, though a previous acquaintance with the elementary properties of tensors will help. Some of the other basic physics topics which have been developed in this book without assuming any previous background are the theory of radiative transfer and the kinetic theory of gravitating particles (using the collisionless Boltzmann equation).

I have followed the usual traditional order of first concentrating on stars and then taking up galaxies to end with extragalactic astronomy and cosmology. One issue about which I had to give some thought is the placement of the basic physics topics which I develop in the book. A possible approach would have been to develop all the necessary basic physics topics at the beginning of the book before delving into the world of astrophysics. I personally felt that a more satisfactory approach is to teach these physics topics 'on the way' as we proceed with astrophysics. Since radiative transfer is used so extensively in astrophysics, it comes fairly early in Chapter 2. Two other chapters dealing primarily with basic physics topics are Chapters 7 and 8 devoted respectively to stellar dynamics and plasma astrophysics. These chapters could conceivably be placed somewhere else in the book. I felt that, after learning about our Galaxy and interstellar matter in Chapter 6, students will be in a position to appreciate stellar dynamics and plasma astrophysics particularly well, before they get into extragalactic astronomy where there will be more applications of what they learn in Chapters 7 and 8. However, putting Chapters 7 and 8 where they are has been ultimately my personal choice without very compelling logical reasons behind it.

Now let me comment on the place of general relativity in my book. The course *Fundamentals of Astrophysics* which I have taught in our department on several occasions does not cover general relativity (we have a separate course *General Relativity and Cosmology* in our department). In the *Fundamentals of Astrophysics* course, I basically cover the material of Chapters 1–11, which is more than sufficient for a one-semester course. In Chapters 10–11, I present as much cosmology as can be done without a detailed technical knowledge of general relativity. Initially my plan was to write up only Chapters 1–11. During the course of writing this book, I decided to add the last three chapters – primarily because general relativity is playing an increasingly more important role in many branches of astrophysics. One of the areas of astrophysics which underwent the most explosive growth in the last decade is the study of the Universe at redshifts $z \geq 1$. Issues involved in the study of the high-redshift Universe cannot be appreciated without some technical knowledge of relativistic astrophysics. Another important development in the last decade has been the construction of several large detectors of gravitational radiation – a consequence of general relativity. Because of the increased applications of general relativity to astrophysics and also for the sake of completeness, I finally decided to write Chapters 12–14. After developing general relativity from the first principles in Chapters 12–13, I discuss relativistic cosmology in Chapter 14. So the presentation of cosmology has been somewhat fractured. Topics which can be developed without a technical knowledge of general relativity are presented in Chapters 10–11, while topics requiring general relativity are presented in Chapter 14. Although this arrangement may be intellectually unsatisfactory, I believe that the advantages outweigh the disadvantages. Readers desirous of learning the basics of cosmology without first learning general relativity can go through Chapters 10–11. Instructors wishing to teach a one-semester course of astrophysics to students who do not know general relativity can use the material of Chapters 1–11. On the other hand, a course on general relativity and cosmology can be based on Chapters 10–14 – with some rearrangement of topics and with the inclusion of additional topics like structure formation, which is barely touched upon in this book. Finally, it should be possible to use this as a basic textbook for a two-semester course on astrophysics and relativity – with some additional material thrown in, depending on the choice of the instructor.

This book has been and will probably remain the most ambitious project I have ever undertaken in my life. While writing my previous book *The Physics of Fluids and Plasmas*, I mostly had to deal with topics on which I had some expertise. Now the canvas is much vaster. It is probably not possible today for an individual to have in-depth knowledge of all branches of modern astrophysics. At least, I cannot claim such knowledge. A writer aspiring to cover the whole of astrophysics is, therefore, compelled to write on many subjects on which his/her own knowledge is shaky. Apart from the risk of making actual technical mistakes, one runs the risk of not realizing where the emphasis should be put. I shall be grateful to any reader who brings any mistake to my attention, by sending an e-mail to my address arnab@physics.iisc.ernet.in. I do hope that readers will find that the merits of this book outnumber its flaws.

Acknowledgments

Apart from my gratitude to many authors whose books I consulted when preparing this book (all these authors are mentioned in *Suggestions for Further Reading*), I am grateful to several outstanding teachers I had as a graduate

student at the University of Chicago in the early 1980s. I was particularly lucky to have courses on *Plasma Astrophysics* from Eugene Parker, *Relativistic Astrophysics* from James Hartle, *Cosmology* from David Schramm and *Stellar Evolution* from David Arnett. The influence which these teachers left on me provided me guidance when I myself had to teach these subjects to my students and this influence must have eventually percolated into this book.

I asked a few colleagues to read those chapters on which I was feeling particularly unsure. Colleagues who made valuable suggestions on some of these chapters are H.C. Bhatt, Sudip Bhattacharyya, K.S. Dwarakanath, Biman Nath, Tarun Deep Saini and Kandaswamy Subramanian. While these colleagues caught many errors which would have otherwise crept into the book, I am sure that this book still has many errors and mistakes for which I am responsible.

Ramesh Babu, Shashikant Gupta and Bidya Binay Karak prepared many of the figures in this book. I am also grateful to many organizations and individuals who permitted me to reproduce figures under their copyright. The acknowledgments are given in the captions of those figures.

I thank the staff of Cambridge University Press (especially Laura Clark, Vince Higgs, Simon Mitton and Dawn Preston) for their cooperation during the many years I took in preparing this book. Many students who have taken this course from me over the years encouraged me by regularly enquiring about the progress of the book and by giving their feedback on the course. A project of this magnitude would not have been possible without the strong support of my wife Mahua. Two persons who would have been the happiest to see this book left us during the long process of writing this book: my mother and my father. This book is dedicated to their memories.

Arnab Rai Choudhuri

A note on symbols

In discussing astrophysical topics, one often has to combine results from different branches of physics. Historically these branches may have evolved independently and sometimes the same symbol is used for different things in these different branches. In the case of a few symbols, I have added a subscript to make them unambiguous. For example, I use $\sigma_{\rm T}$ for the Thomson cross-section (since σ denotes the Stefan–Boltzmann constant), $\kappa_{\rm B}$ for the Boltzmann constant (since k denotes the wavenumber in several derivations) and $a_{\rm B}$ for the blackbody radiation constant (since a denotes the scale factor of the Universe). A look at equation (3.48) of Kolb and Turner (1990) will show the kinds of problems you run into if you use the same symbol to denote different things in a derivation. While I have avoided using the same symbol for different things within one derivation, I sometimes had to use the same symbol for different things in different portions of the book. For example, it has been the custom for many years to use M to denote both mass (of stars or galaxies) and absolute magnitude. Rather than inventing unorthodox symbolism, I have trusted the common sense of readers who should be able to figure out the meaning of the symbol from the context and hopefully will not get confused. I now mention a potential source of confusion. I have used $f(E)$ in §4.2 to denote the probability that particles have energy E and have used $f(p)$ in §5.2 to denote the number density of particles with momentum p (throughout Chapter 7, I use f to denote number density and not probability). While these notations may not be consistent with each other, they happen to be the most convenient notations for the derivations presented in §4.2 and §5.2 (and also the notations used by many previous authors).