Course of Theoretical Astrophysics

Volume I: Astrophysical Processes

Graduate students and researchers in astrophysics and cosmology need a solid understanding of a wide range of physical processes. This clear and authoritative textbook has been designed to help them to develop the necessary toolkit of theory. Assuming only an undergraduate background in physics and no detailed knowledge of astronomy, this book guides the reader step by step through a comprehensive collection of fundamental theoretical topics. The book is modular in design, allowing the reader to pick and choose a selection of chapters, if necessary. It can be used alone or in conjunction with the forthcoming accompanying two volumes (covering stars and stellar systems and galaxies and cosmology, respectively).

After the basics of dynamics, electromagnetic theory, and statistical physics are reviewed, a solid understanding of all the key concepts such as radiative processes, spectra, fluid mechanics, plasma physics and magnetohydrodynamics, dynamics of gravitating systems, general relativity, and nuclear physics is developed. Each topic is developed methodically from undergraduate basic physics. Throughout, the reader's understanding is developed and tested with carefully structured problems and helpful hints.

This welcome volume provides graduate students with an indispensable introduction to and reference on all the physical processes they will need to tackle successfully cutting-edge research in astrophysics and cosmology.

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COURSE OF THEORETICAL ASTROPHYSICS

Volume I: Astrophysical Processes

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Dedicated to the memory of L.D. Landau,
who understood the importance of pedagogy

COURSE OF THEORETICAL ASTROPHYSICS

– in three volumes –

VOLUME I: ASTROPHYSICAL PROCESSES

1: Order-of-magnitude astrophysics; 2: Dynamics; 3: Special Relativity, Electrodynamics, and Optics; 4: Basics of Electromagnetic Radiation; 5: Statistical Mechanics; 6: Radiative Processes; 7: Spectra; 8: Neutral Fluids; 9: Plasma Physics; 10: Gravitational Dynamics; 11: General Theory of Relativity; 12: Basics of Nuclear Physics.

VOLUME II: STARS AND STELLAR SYSTEMS

1: Overview: Stars and Stellar Systems; 2: Stellar Structure; 3: Stellar Evolution; 4: Supernova; 5: White Dwarfs, Neutron Stars, and Black Holes; 6: Pulsars; 7: Binary Stars and Accretion; 8: Sun and Solar System; 9: Interstellar Medium; 10: Globular Clusters.

VOLUME III: GALAXIES AND COSMOLOGY

1: Observational Overview; 2: Galactic Structure; 3: Galactic Dynamics and Interactions; 4: Friedmann Model; 5: Active Galactic Nuclei–Structural Aspects; 6: Thermal History of the Universe; 7: Structure Formation; 8: Cosmic Microwave Background Radiation; 9: Formation of Baryonic Structures; 10: Active Galactic Nuclei–Cosmological Aspects; 11: Intergalactic Medium and Absorption Systems; 12: Cosmological Observations.

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Preface

"...yoyum varo gudham anupravisto,
naanyam thasman Nachiketa vrinithe."
("...Nachiketa does not choose any other boon but
[learning about] that of which Knowledge is hidden.")

Katho Upanishad, Verse 29.

During the past decade or so, theoretical astrophysics has emerged as one of the most active research areas in physics. This advance has also been reflected in the greater interdisciplinary nature of research that is being carried out in this area in the recent years. As a result, those who are learning theoretical astrophysics with the aim of making a research career in this subject need to assimilate considerable amount of concepts and techniques, in different areas of astrophysics, in a short period of time. Every area of theoretical astrophysics, of course, has excellent textbooks that allow the reader to master that *particular* area in a well-defined way. Most of these textbooks, however, are written in a traditional style, focussing on one area of astrophysics (say stellar evolution, galactic dynamics, radiative processes, cosmology etc.) Because different authors have different perspectives regarding their subject matter it is not very easy for a student to understand the key unifying principles behind several different astrophysical phenomena by studying a plethora of separate textbooks, as they do not link up together as a series of core books in theoretical astrophysics covering everything which a student would need. A few books, which *do* cover the whole of astrophysics, deal with the subject at a rather elementary ("first course") level.

What we require is clearly something analogous to the famous Landau–Lifshitz course in theoretical physics, but focussed to the subject of theoretical astrophysics at a fairly advanced level. In such a course, all the key physical concepts (e.g., radiative processes, fluid mechanics, plasma physics, etc.) can be presented from a unified perspective and then applied to different astrophysical situations.

This book is the first of a set of three volumes that are intended to do exactly that. They form one single coherent unit of study through the use of which a student can acquire mastery over all the traditional astrophysical topics. What is more, these volumes emphasise the unity of concepts and techniques in different branches of astrophysics. The interrelationship among different areas and common features in the analysis of different theoretical problems will be stressed throughout. Because many of the basic techniques need to be developed only once, it is possible to achieve a significant economy of presentation and crispness of style in these volumes.

Needless to say, there are some basic "boundary conditions" one has to respect in such an attempt to cover the whole of Theoretical Astrophysics in approximately 3×580 pages. Not much space is available to describe the nuances in greater length or to fill in the details of algebra. For example, I have made conscious choices as to which parts of the algebra can be left to the reader and which need to be worked out explicitly in the text, and I have omitted a detailed discussion of elementary concepts and derivations. However, I do *not* expect the reader to know anything about astrophysics. All astrophysical concepts are developed ab initio in these volumes. The approach used in these three volumes is similar to that used by Gengis Khan, namely, (1) cover as much area as possible, (2) capture the important points, and (3) be utterly ruthless!

To cut out as much repetition as possible, the bulk of the physical principles are presented at one go in Vol. I and are applied in the other two volumes to different situations. This implies that there will be a lot of physics but very little of "concrete" astrophysics in Vol. I; that comes in Vol. II (Stars and Stellar Systems) and Vol. III (Extragalactic Astronomy and Cosmology). The criteria for the selection of material for Vol. I have been the following: (1) Any physical principle that finds application in more than one chapter of Vol. II or Vol. III (for example, bremsstrahlung, Voigt profile, etc.) is discussed in Vol. I. Certain topics that are used in only a specific chapter in Vol. II or Vol. III are discussed in situ rather than in Vol. I. (2) By and large, everything discussed in Vol. I will be utilized directly somewhere in Vols. II and III. On rare occasion, I do cover a topic in Vol. I even if it is not fully utilized in Vol. II or Vol. III because a reader who is going to work in theoretical astrophysics will eventually need an understanding of that particular topic. (3) These three volumes concentrate on *theoretical* aspects. Observation and phenomenology are, of course, discussed in Vols. II and III to the extent necessary to make the motivation clear. However, I do not have the space to discuss how these observations are made, the errors, reliability, etc., of the observations or the astronomical techniques. (Maybe there should be a fourth volume describing observational astrophysics!)

The target audience for this three-volume work will be fairly large and is made up of (1) students in the first year of their Ph.D. Program in theoretical physics, astronomy, astrophysics, and cosmology; (2) research workers in various fields of theoretical astrophysics, cosmology, etc.; and (3) teachers of graduate courses in theoretical astrophysics, cosmology and related subjects. In fact, anyone working in or interested in some area of astronomy or astrophysics will find something useful in these volumes. They are also designed in such a way that parts of the material can be used in modular form to suit the requirements of different people and different courses.

Let me briefly highlight the features which are specific to Vol. I. The reader of Vol. I is assumed to have done basic courses in classical mechanics, nonrelativistic quantum mechanics, and classical electromagnetic theory. Of the 12 chapters in Vol. I, the first one is a broad-brush overview of physical principles in an order-of-magnitude manner and is intended to set the stage. I expect the reader to survey this chapter rapidly but to come back to it periodically at later stages. This chapter is probably the easiest or the most difficult, depending on one's background and aptitude. It is easy in the sense that very little sophisticated mathematics is used; difficult because it takes a high level of maturity to appreciate some of the physical arguments that are presented. Chapters 2 (Dynamics), 3 (Special Relativity, Electrodynamics, and Optics), and 5 (Statistical Mechanics) cover the ground the reader may already be familiar with – but from an advanced perspective. The aim is to introduce powerful techniques in familiar contexts so that the reader can learn and appreciate them. For example, no apologies are made for introducing four-vector notation up front or dealing with distribution functions right from the beginning, so as to get the main results as quickly as possible. The emphasis throughout is on topics relevant in astrophysics, such as the reduced three-body problem, action-angle variables, diffraction and interference, optical systems, propagation in random media, ionisation equilibria, etc. Chapter 4 deals with the basics of radiation theory – both classical and quantum – that is developed from scratch and the reader is *not* assumed to be familiar with quantum field theory.

Chapters 6–12 develop the toolkit for astrophysics in a self-contained manner, virtually ab initio. Chapters 6 (Radiative Processes) and 8 (Fluid Mechanics) are fairly exhaustive and detailed. The short chapter on Spectra (Chap. 7) covers general material that is of astronomical relevance; more specific aspects will be dealt with in Vols. II and III within the appropriate contexts. In Chap. 9 (Plasma Physics) I had to make choices as to which topics are of sufficiently general nature to appear in Vol. I; some specific topics (e.g., instability of axisymmetric systems with magnetic fields, alpha effect, and dynamos) will appear in the relevant chapters of Vols. II and III. Chapter 10 (Gravitational Dynamics) covers the background needed for galactic dynamics, globular cluster evolution, etc. Chapter 11 is a compact introduction to general relativity and *no* previous familiarity with tensor analysis is assumed. Finally, Chap. 12 deals with aspects of nuclear physics that are needed in the study of stellar evolution.

Any one of these topics is fairly vast and often requires a full textbook to do justice to it, whereas I have devoted approximately 60 pages to each of them!

I would like to emphasise that such a crisp, condensed discussion is not only possible but also constitutes a basic matter of policy in these volumes. After all, the idea is to provide the student with the essence of several textbooks in one place. It should be clear to lecturers that these material can be easily regrouped to serve different graduate courses at different levels, especially when complemented by other textbooks.

Because of the highly pedagogical nature of the material covered in Vol. I, I have not given detailed references to original literature except on rare occasions when a particular derivation is not available in standard textbooks. The annotated list of references given at the end of the book cites several other textbooks that I found very useful. Some of these books, of course, contain extensive bibliographies and references to original literature. The selection of core books cited here clearly reflects the personal bias of the author and I apologise to anyone who feels that their work or contribution has been overlooked.

Several people have contributed to the making of these volumes and especially to Vol. I. The idea for these volumes originated over a dinner with J.P. Ostriker in late 1994, while I was visiting Princeton. I was lamenting to Jerry about the lack of a comprehensive set of books covering all of theoretical astrophysics and Jerry said, “Why don’t *you* write them?” He was very enthusiastic and supportive of the idea and gave extensive comments and suggestions on the original outline I produced in the next one week. I am grateful to him for the comments and for the moral support that I needed to launch into such a project. I sincerely hope the volumes do not disappoint him.

Adam Black of Cambridge University Press took up the proposal with his characteristic enthusiasm and initiative; this is the third project on which we worked together and I thoroughly enjoyed it. I should also thank him for choosing six excellent (anonymous) referees for this proposal whose support and comments helped to mould the proper framework.

Many of my friends and colleagues carried out the job of reading the earlier drafts and providing comments. Of these, M. Vivekanand has gone through most of the book with meticulous care and has given extensive comments. Many other colleagues, especially Roger Blandford, George Djorgovsky, Peter Goldreich, John Huchra, Donald Lynden-Bell, J.V. Narlikar, R. Nityananda, Sterl Phinney, and Douglas Richstone looked at the whole draft and provided comments and suggestions at different levels of detail. J.S. Bagla, Sai Iyer, Nissim Kanekar, Ben Oppenheimer, K. Subramanian, S. Sankaranarayanan, and K. Srinivasan gave detailed comments on selected chapters; the last two took pains to check most of the derivations and algebraic expressions. I thank all of them for their help.

I have been visiting the Astronomy Department of Caltech during the past several years and the work on this book has benefitted tremendously through my discussions and interactions with the students and staff of the Caltech Astronomy Department. I especially thank Roger Blandford, Peter Goldreich, Shri Kulkarni,

Sterl Phinney, and Tony Readhead for several useful discussions and for sharing with me their insights and experience in physics teaching.

This project would not have been possible but for the dedicated support from Vasanthi Padmanabhan, who not only did the entire TEXing and formatting but also produced most of the figures – often writing the necessary programs for the same. I thank her for the help and look forward to receiving the same for the next two volumes! I also thank Sunu Engineer who was resourceful in solving several computer-related problems that cropped up periodically. It is a pleasure to acknowledge the library and other research facilities available at the Inter-University Centre for Astronomy and Astrophysics, which were useful in this task.

T. Padmanabhan