Theoretical Astrophysics

Volume III: Galaxies and Cosmology

This timely volume provides comprehensive coverage of all aspects of cosmology and extragalactic astronomy at an advanced level. Beginning with an overview of the key observational results and necessary terminology, it goes on to cover important topics including the theory of galactic structure and galactic dynamics, structure formation, cosmic microwave background radiation, formation of luminous galaxies in the universe, intergalactic medium, and active galactic nuclei. Topics are developed in a contemporary fashion, with emphasis on currently active research areas.

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THEORETICAL ASTROPHYSICS

Volume III: Galaxies and Cosmology

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Frontmatter
More Information

To all my friends

THEORETICAL ASTROPHYSICS

– in three volumes –

VOLUME I: PHYSICAL PROCESSES

Chapters 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

Chapters 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

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

Contents

Preface

From where has this Creation sprung ? Who holds or does not hold ?
He who is its Surveyer in the highest heaven, He alone knows
And yet maybe He doth not know ?

— Rig Veda, Verse 10.129.7.

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 has been carried out in this area in 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 a 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 that focusses 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 that 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, one could present all the key physical concepts (eg. radiative processes, fluid mechanics, plasma physics,

etc.) from a unified perspective and then apply them to different astrophysical situations.

This book is the third in a set of three volumes that are intended to do exactly that. The three volumes form one single coherent unit of study, using which a student can acquire mastery over all the traditional astrophysical topics. What is more, these volumes will 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 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 3×600 pages. Not much space is available to describe the nuances in greater length or to fill in 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 parts need to be worked out explicitly in the text, and I have omitted detailed discussions 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 Genghis Khan, namely (*i*) cover as much area as possible, (*ii*) capture the important points, and (*iii*) 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. These three volumes also 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 comprises: (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 that are specific to Vol. III. The reader is assumed to be familiar with the material covered in Vol. I, having either studied that volume (which is the recommended procedure!) or through independent courses in basic physics. This volume also uses several topics developed in

Vol. II; for example, the discussion of accretion disks (in Chap. 7 of Vol. II) and the interstellar medium (Chap. 9 of Vol. II) finds application in the study of active galactic nuclei and the intergalactic medium. The spirit of the three coherent volumes is to avoid repetition as much as possible, and hence I have merely referred to the relevant parts of Vol. I or Vol. II whenever some input is required. Given this background, it was fairly easy to order the topics of Vol. III in a logical sequence, and I have broadly followed the same format as that of Vol. II. Chapter 1 provides a broad overview of galaxies and cosmology and rapidly introduces several observational and theoretical concepts that are developed in detail in the later chapters. This is done to tackle the interdependency of concepts (and jargon) that prevents the development of topics in a fully streamlined fashion. I expect the reader to rapidly go through Chap. 1 in the first reading and come back to it as and when required. Chapter 2 introduces several aspects of galactic structure and dynamics, building on the observational inputs already covered in Chap. 1. Chapters 3–5 form the core of cosmology and structure formation. The logical structure is somewhat similar to the one I adopted in my 1993 book *Structure Formation in the Universe*, but I have updated the contents quite significantly, keeping in mind the nature of these volumes as well as recent developments. For example, I have included a discussion of models with a nonzero cosmological constant that are enjoying considerable popularity at present. I have also added a somewhat simple discussion of different gauges that are used in the study of structure formation. Chapter 6 deals with cosmic microwave background radiation, which will continue to attract attention in the coming years. Even as this chapter was being written, data from CMBR experiments were revised, necessitating my rewriting of the chapter. Quite obviously, the details and the comparison with observation will not survive for long, but I have tried to present the fundamental issues in such a way that they will have a much longer shelf life. Chapter 7 deals with the actual formation of luminous galaxies in the universe, which is probably one of the most complex topics under active investigation. I have refrained from quoting results of numerical simulations mainly because I do not believe the hydrosimulations have yet reached a stage to warrant inclusion in a basic textbook like this. Instead, I have tried to give semianalytic arguments and qualitative descriptions to give the reader a flavour of our current understanding of this difficult subject. Chapter 8 takes a detour to describe the important features of active galactic nuclei. I have drawn heavily on the material developed in earlier volumes (in particular, as regards radiative processes and physics of accretion disks) and have tried to give a coherent picture of active galactic nuclei in different wave bands. Chapter 9 describes the physics of intergalactic medium and absorption systems; once again, the emphasis is on relatively modern topics like the role of star formation and the production of extragalactic background light. Finally, Chap. 10 provides a rapid overview of observations relevant to cosmology and the techniques used to measure different cosmological parameters. This chapter also includes a discussion of the evidence for dark matter in different scales.

This volume also provided a tough challenge as regards the discussion of phenomenological input and a few words regarding my policy are in order. I have followed essentially the same philosophy as I used in Vol. II and have tried to avoid the two pitfalls: (1) Drowning the reader in accurate but unclassified sea of astronomical data just because accurate data are available or (2) ignoring the phenomenological input and treating the subject as a branch of applied mathematics – a criticism I have heard as regards my book *Structure Formation in the Universe*. As in Vol. II, I have tried to describe the necessary observational issues (but not observational techniques) and provide a minimum of observational data whenever it is relevant. I have also tried to motivate theoretical developments based on specific observational inputs, especially when a more fundamental approach would be unwarranted or facetious. At the same time I have tried to bring some amount of method and order to the presentation of the topics so that the reader will be able to grasp how a theoretical astrophysicist goes about the task of developing the models. (Once again, this makes Chap. 1 somewhat different in form and content compared with other chapters. I hope this is not too much of a distraction.)

All this required the exercise of my judgement in deciding the choice of topics, their emphasis, and the proper blend of phenomenology, observations, and theoretical rigour. It is impossible to satisfy everyone as regards the "correctness" of such decisions, and I have tried to do some optimisation so as to provide maximum benefit to the reader. The two topics that I probably would have liked to discuss at length but had to forego are the physics of cosmic rays and the stucture and dynamics of galaxy clusters. Except for these, I believe I have done justice to most of the topics at a level appropriate for these volumes.

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 discuss 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 materials 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 this volume, 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 their work or contribution has been overlooked.

Several people have contributed to the making of these volumes. 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 the next 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 (who was with Cambridge University Press at that time) took up the proposal with his characteristic enthusiasm and initiative. I should also thank him for choosing six excellent (anonymous) referees for this proposal whose support and comments helped to mould it into the proper framework. The processing of this volume was handled by Simon Mitton of Cambridge University Press, and I thank him for the effort he has put in.

Many of my friends and colleagues carried out the job of reading the earlier drafts and providing comments. Many colleagues, especially Jaichan Hwang, Chanda Jog, Ofer Lahav, Niranjan Sambhus, Shiv Sethi, T. Souradeep, R. Srianand, K. Subramanian, and Yogesh Wadedekar, have made comments on selected chapters. Some of the figures and data were provided by C.W. Churchill, Tapas Kumar Das, George Djorgovski, Bill Keel, John Peacock, Niranjan Sambhus, Shiv Sethi, and C.C. Steidel, and I thank them for their help.

I have been a regular visitor to the Astronomy department of Caltech during the past several years, and the work on the volumes has benefitted tremendously through my discussions and interactions with the students and staff of the Caltech Astronomy department. I would like to specially 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 the teaching of astrophysics. Part of the work on this volume was done while I was visiting the Institute of Astronomy, Cambridge, England, in May 2001.

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 in all three volumes. It is a pleasure to acknowledge the library and other research facilities available at IUCAA, which were useful in this task.

T. Padmanabhan