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# Extragalactic Astronomy and Cosmology



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Peter Schneider

# Extragalactic Astronomy and Cosmology

An Introduction

Second Edition

 Springer

Peter Schneider  
Argelander-Institut für Astronomie  
Universität Bonn  
Bonn  
Germany

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*For Mónica*



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## Preface

Amazing times! I finished the manuscript for the first edition of this book just 8 years ago—but the necessity of a new edition was urgently felt. In these years we have witnessed an enormous development in the field of extragalactic astronomy and cosmology. On the instrument side, the final servicing mission to the Hubble Space Telescope brought two new very powerful instruments to this unique observatory, the Herschel and Planck satellites were launched and conducted their very successful missions, the South Pole Telescope and the Atacama Cosmology Telescope started operation, ALMA was inaugurated and began observations, and new powerful high-resolution instruments were installed on 10-m class telescopes. Scientifically, the redshift frontier has been extended, with candidate galaxies at redshifts of ten or higher and stellar explosions seen at redshifts beyond eight, a much improved understanding of the high-redshift galaxy population has been obtained, as a consequence of which also the origin of the cosmic infrared background is now understood, and greatly improved multi-wavelength surveys carried out with the most powerful telescopes, together with new simulation techniques, have provided us with a much better understanding of the evolution of the galaxy population. The Pierre Auger observatory has shed much light on the origin of the most energetic cosmic rays, and the advances of atmospheric Cherenkov telescopes have identified dozens of active galaxies emitting at energies of teraelectron Volts.

Several blind surveys have detected galaxy clusters by their Sunyaev–Zeldovich effect, providing a new and powerful route for cluster cosmology. WMAP has finished its 9 years of surveying the microwave sky, and confirmed two of the predictions of inflation—the spatial flatness of our Universe and the finite tilt of the initial power spectrum. The first cosmological results from Planck were stunning, including an all-sky map of the gravitational potential which is responsible for lensing the cosmic microwave background. The use of baryonic acoustic oscillations as a standard rod to measure the geometry of our Universe has by now been firmly established. Two Nobel prizes in physics, given to cosmologists in 2006 and 2011 for studies of the cosmic microwave background and for the discovery of the accelerated expansion of the Universe using Type Ia supernovae, highlight the impact of this science in the broader physics context.

In this second edition, I have tried to account for these new developments, by updating and (in some cases, substantially) expanding many sections. New material has been added, including a separate chapter on galaxy evolution, as well as sections on the standard model of elementary particles and WIMPs as dark matter candidates, properties of high-redshift galaxies and the galaxy population in clusters, and several other topics. Following the suggestion of several reviewers of the first edition, problems (and solutions) have been added to most chapters. However, I have tried to preserve the style and level of the original book, aiming at a text which combines the physical exploration of cosmic objects with the fascination of astronomical and cosmological research.

I thank Frank Bertoldi, Thomas Reiprich, and Mónica Valencia for carefully reading selected chapters and their numerous helpful suggestions, as well as several colleagues who mailed comments to the first edition. Norbert Wermes provided very useful comments on the particle physics section. I would like to thank Sandra Unruh for her invaluable help in preparing this edition, including numerous comments on draft versions and her efforts to attain the right

to reproduce the many new figures from colleagues all over the world. The collaboration with Ramon Khanna of Springer-Verlag continued to be very constructive.

This book could not have been realized without the many expert colleagues from around the world who agreed that their original figures be reproduced here. I thank them sincerely for that and hope that I have represented their original work in a fair way.

I very much appreciate the patience and understanding of my colleagues, in particular my students, for my highly reduced availability and level of activity on other issues during the final months of preparing the manuscript. Finally, I very much thank my wife Mónica for her love, her encouragement, and her support.

Bonn, Germany  
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Peter Schneider

### **From the first edition**

This book began as a series of lecture notes for an introductory astronomy course I have been teaching at the University of Bonn since 2001. This annual lecture course is aimed at students in the first phase of their studies. Most are enrolled in physics degrees and choose astronomy as one of their subjects. This series of lectures forms the second part of the introductory course, and since the majority of students have previously attended the first part, I therefore assume that they have acquired a basic knowledge of astronomical nomenclature and conventions, as well as on the basic properties of stars. Thus, in this part of the course, I concentrate mainly on extragalactic astronomy and cosmology, beginning with a discussion of our Milky Way as a typical (spiral) galaxy. To extend the potential readership of this book to a larger audience, the basics of astronomy and relevant facts about radiation fields and stars are summarized in the appendix.

The goal of the lecture course, and thus also of this book, is to confront physics students with astronomy early in their studies. Since their knowledge of physics is limited in their first year, many aspects of the material covered here need to be explained with simplified arguments. However, it is surprising to what extent modern extragalactic astronomy can be treated with such arguments. All the material in this book is covered in the lecture course, though not all details written up here. I believe that only by covering this wide range of topics can the students be guided to the forefront of our present astrophysical knowledge. Hence, they learn a lot about issues which are currently unsettled and under intense discussion. It is also this aspect which I consider of great importance for the role of astronomy in the framework of a physics program, since in most other subdisciplines of physics the limits of our current knowledge are approached only at a later stage in the education.

In particular, the topic of cosmology is usually met with interest by the students. Despite the large amount of material, most of them are able to digest and understand what they are taught, as evidenced from the oral examinations following this course—and this is not small-number statistics: my colleague Klaas de Boer and I together grade about 100 oral examinations per year, covering both parts of the introductory course. Some critical comments coming from students concern the extent of the material as well as its level. However, I do not see a rational reason why the level of an astronomy lecture should be lower than that of one in physics or mathematics.

Why did I turn this into a book? When preparing the concept for my lecture course, I soon noticed that there is no book which I can (or want to) follow. In particular, there are only a few astronomy textbooks in German, and they do not treat extragalactic astronomy and cosmology nearly to the extent and depth as I wanted for this course. Also, the choice of books on these topics in English is fairly limited—whereas a number of excellent introductory textbooks exist, most shy away from technical treatments of issues. However, many aspects can be explained

better if a technical argument is also given. Thus I hope that this text presents a field of modern astrophysics at a level suitable for the aforementioned group of people. A further goal is to cover extragalactic astronomy to a level such that the reader should feel comfortable turning to more professional literature.

When being introduced to astronomy, students face two different problems simultaneously. On the one hand, they should learn to understand astrophysical arguments—such as those leading to the conclusion that the central engine in AGNs is a black hole. On the other hand, they are confronted with a multitude of new terms, concepts and classifications, many of which can only be considered as historical burdens. Examples here are the classification of supernovae which, although based on observational criteria, do not agree with our current understanding of the supernova phenomenon, and the classification of the various types of AGN. In the lecture, I have tried to separate these two issues, clearly indicating when facts are presented where the students should ‘just take note’, or when astrophysical connections are uncovered which help to understand the properties of cosmic objects. The latter aspects are discussed in considerably more detail. I hope this distinction can still be clearly seen in this written version.

The order of the material in the course and in this book accounts for the fact that students in their first year of physics studies have a steeply rising learning curve; hence, I have tried to order the material partly according to its difficulty. For example, homogeneous world models are described first, whereas only later are the processes of structure formation discussed, motivated in the meantime by the treatment of galaxy clusters.

The topic and size of this book imply the necessity of a selection of topics. I want to apologize here to all of those colleagues whose favorite subject is not covered at the depth that they feel it deserves. I also took the freedom to elaborate on my own research topic—gravitational lensing—somewhat disproportionately. If it requires a justification: the basic equations of gravitational lensing are sufficiently simple that they and their consequences can be explained at an early stage in the astronomy education.

Many students are not only interested in the physical aspects of astronomy, they are also passionate observational astronomers. Many of them have been active in astronomy for years and are fascinated by phenomena occurring beyond the Earth. I have tried to provide a glimpse of this fascination at some points in the lecture course, for instance through some historical details, by discussing specific observations or instruments, or by highlighting some of the great achievements of modern cosmology. At such points, the text may deviate from the more traditional ‘scholarly’ style.

Producing the lecture notes, and their extension to a textbook, would have been impossible without the active help of several students and colleagues, whom I want to thank here. Jan Hartlap, Elisabeth Krause, and Anja von der Linden made numerous suggestions for improving the text, produced graphics or searched for figures, and  $\text{\TeX}$ ed tables—deep thanks go to them. Oliver Czoske, Thomas Erben, and Patrick Simon read the whole German version of the text in detail and made numerous constructive comments which led to a clear improvement of the text. Klaas de Boer and Thomas Reiprich read and commented on parts of this text. Searching for the sources of the figures, Leonardo Castaneda, Martin Kilbinger, Jasmin Pierloz, and Peter Watts provided valuable help. A first version of the English translation of the book was produced by Ole Markgraf, and I thank him for this heroic task. Furthermore, Kathleen Schrüfer, Catherine Vlahakis, and Peter Watts read the English version and made zillions of suggestions and corrections—I am very grateful to their invaluable help. Finally, I thank all my colleagues and students who provided encouragement and support for finishing this book.

The collaboration with Springer-Verlag was very fruitful. Thanks to Wolf Beiglböck and Ramon Khanna for their encouragement and constructive collaboration. Bea Laier offered to contact authors and publishers to get the copyrights for reproducing figures—without her invaluable help, the publication of the book would have been delayed substantially. The interaction with  $\text{\LaTeX}$ , where the book was produced, and in particular with Uwe Matrisch, was constructive as well.

Furthermore, I thank all those colleagues who granted permission to reproduce their figures here, as well as the public relations departments of astronomical organizations and institutes who, through their excellent work in communicating astronomical knowledge to the general public, play an invaluable role in our profession. In addition, they provide a rich source of pictorial material of which I made ample use for this book. Representative of those, I would like to mention the European Southern Observatory (ESO), the Space Telescope Science Institute (STScI), the NASA/SAO/CXC archive for Chandra data, and the Legacy Archive for Microwave Background Data Analysis (LAMBDA).

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