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James Rich

Fundamentals of Cosmology

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and 68 Problems with 23 Selected Solutions

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Preface

This is a textbook intended for students and researchers who wish to understand the physics of standard "big bang" cosmology and how it is used to interpret the most recent observations. It is based on courses given over the last seven years to beginning graduate students at the University of Paris and to advanced undergraduates at l'Ecole Polytechnique. Since the great majority of these students did not intend to become professional cosmologists, I have emphasized subjects that should be of general interest.

Progress in observations over the last ten years has been truly astounding and a new textbook might be justified simply to report on recent breakthroughs. The traditional successes of modern cosmology are well-known. Among these are the dynamical understanding of the universal expansion, the prediction of the cosmic microwave background radiation, and the calculation of the abundances of the light elements. To these we can add new observations that suggest that we are beginning the era of "precision cosmology." Perhaps most spectacular was the observation this year of the first acoustic peak in the anisotropy spectrum of the cosmic background radiation by the Boomerang and Maxima collaborations. These beautiful measurements have convinced many people that the universe has a nearly critical energy density and that a complete understanding of structure formation may be at hand.

While a critical density was expected by many cosmologists, the observed breakdown into different components has revolutionary implications. Observations during the last decade have confirmed that most of the matter that is bound in galaxies or galaxy clusters is in some unknown form. Many cosmologists believe that the observations indicate the existence of "cold dark matter", most likely some as yet undetected weakly interacting massive particle. Cold dark matter has been a standard fixture on the conference circuit for nearly twenty years, and we sometimes forget how daring this prediction is.

More revolutionary still is the conclusion, based on the observed fluxes from high-redshift supernovae, that the expansion of the universe is accelerating. Within standard gravitational theory, this implies that the energy content of the universe is dominated by an effective vacuum energy or, equivalently, a cosmological constant. Being a new form of energy not directly associated with an elementary particle, this discovery, if confirmed, would rank in theoretical importance with the discovery of, say, electromagnetic fields.

Observations during the next decade will provide precision tests of this picture of a universe dominated by cold dark matter and vacuum energy. A more difficult problem is to determine whether these two substances are "elements of reality" or just elements of theories. Even if the Universe *acts* like a universe governed by general relativity with a mixture of cold dark matter and vacuum energy, it is possible that nature has fooled us because of our ignorance of a key ingredient. For example, a model using only ordinary matter but with some sort of "modified gravity" operating at cosmological scales might also agree with observations. Some have argued that this is suggested by the fact that models using the simplest cold dark matter particles apparently do not accurately predict the structure of galactic cores or the number of small galaxies. Time will tell if these objections to the standard model hold up. If they do, things will be quite confusing if we have to rely on cosmological observations to *determine* the correct laws of gravity. It would be better if someone settles the question by directly detecting the dark-matter particles.

Given the fascinating questions addressed by cosmology and the great interest aroused by vigorous observational programs, it is not surprising that many students wish to study the subject before completely mastering the necessary background from observational astronomy and astrophysics, elementary particle physics, nuclear physics, and general relativity. This book is an attempt to address this problem.

General relativity is certainly the most difficult aspect of cosmological theory and it presents a formidable pedagogical challenge for an introductory course. Originally, I used the usual Newtonian derivations of the Friedmann equation but this is ultimately unsatisfying. Finally, I have adopted the strategy of presenting a self-contained introduction to relativistic gravitation that uses only the mathematics that is absolutely necessary for cosmology. This is possible because of the extreme simplicity of homogeneous cosmology. We will obtain all the results we need without mentioning affine connections or covariant derivatives.

While attempting to be "relativistically correct", I have adopted a strictly phenomenological point of view of general relativity where the mathematics never strays far from observations made with clocks and radar ranging devices. For instance, comoving coordinates are defined operationally before finding the Robertson–Walker metric from general considerations of symmetry. This strategy is meant to attack what appears to be one of the greatest difficulties of general relativity, connecting all those symbols with the measurements.

In the same phenomenological spirit, in one chapter we abandon the usual comoving coordinates and adopt a simple system that can be constructed operationally by one freely falling observer. In such coordinates, the metric is locally Lorentzian, and many things that are mysterious in comoving coordinates become relatively clear. In particular, it is easy to derive the Friedmann equation, and the nature of the mysterious vacuum energy is made at least plausible.

Concerning elementary particle physics and nuclear physics, I have mostly taken the point of view that these disciplines exist simply to furnish cosmologists with a list of known and hypothetical particles and the values of their cross-sections. Hence, I have not attempted any detailed theoretical introduction to these two fascinating subjects. Speculative subjects like supersymmetric dark matter and inflationary and quintessential scalar fields are treated phenomenologically with only brief mention of the difficulties encountered in integrating them into a coherent theory of particle physics.

Finally, concerning astronomy and astrophysics, I have tried to provide the minimum background necessary to understand the observations. Measurements are often presented in relatively undigested forms so that students can get a feeling for the quality of the data and the difficulty in analyzing it. The importance of hypotheses used in the interpretation of the often ambiguous astrophysical data is emphasized.

I have not gone upstream of the data to discuss observing techniques. This means that I have not presented in the detail it deserves the important technological advances that have made the observations possible. Among these advances we can mention the new generation of 10-m-class telescopes and the Hubble Space Telescope that have given us a much clearer visual view of distant objects. Space-based X-ray telescopes have permitted the detailed study of galaxy clusters, the largest bound objects in the universe. All these telescopes have generated enormous amounts of high-quality data because of advances in photon detection technology. Most obvious are the new CCDs that have gradually replaced traditional photographic plates. Large CCD mosaics have permitted the discovery of high-redshift supernovae, the completion of enormous redshift surveys, and the mapping of mass distributions through weak gravitational lensing. We mention also the new cryogenic bolometers that were used in the measurements of Boomerang and Maxima, and that may someday allow the detection of dark-matter particles.

It has also not been possible to discuss the techniques of computer simulations that are so important for the understanding of structure formation. Our discussion of this process will be, therefore, quite qualitative. We do not touch the unsolved problem of how star-formation is first triggered, creating the observable universe of galaxies. Until astronomers succeed in completely determining the matter distribution of the Universe using gravitational lensing, this problem will continue to plague structure studies based on counting visible galaxies.

Finally, I have not reviewed the history of modern cosmology. This story starts with the discovery of the universal expansion by Hubble and its interpretation by Lemaitre. It is followed by Gamow's theory of primordial nucleosynthesis and the prediction of the cosmic background radiation and the confirming observations of Penzias and Wilson. This story is, by now, well-known so I have mostly ignored it. As a result, references to pioneering work have been perhaps neglected in favor of the most recent work.

Many people have made contributions to this work. Most important are my students at the DEA de Champs, Matière et Particules and the DEA de Physique Théorique. The questions that they asked and the questions that I thought they might ask have constantly challenged me. Special thanks to the student who glared at me when I told her that if she wanted to know where the Friedmann equation comes from she should take a class in general relativity. Chapters 3 and 4 sprang from that tense moment.

This book would never have become a book without the encouragement and advice of Jean-Louis Basdevant. He also suggested that I try it out on undergraduates, an experience that forced me to clarify much of the basic physics.

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Gif-sur-Yvette, *James Rich*
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