Chapter 1

INTRODUCTION

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Every so often in the history of physics a golden opportunity for great progress becomes apparent to contemporary physicists. In the twentieth century, enormous progress was made when, for example, the regularities of atomic spectra became apparent, when the Lamb shift was measured, and when the symmetries of supposedly elementary particles were recognized.

The enigma of dark matter represents a challenge and an opportunity on the same scale as the great physics advances of the twentieth century. Researchers living today are lucky because they can participate in the effort to understand the enigmatic dark matter.

What is the dark matter? It seems very likely that the answer to this question will be of fundamental significance for physics and for astronomy and perhaps for all of science. After all, most of the matter that we know about in the Universe is dark, i.e., we have not been able to detect it yet with our telescopes or other measuring devices. Understanding dark matter will refocus astronomy research and may reveal new types of fundamental particles, e. g., supersymmetric analogues of the known particles.

In 1986, Steven Weinberg and I organized the Fourth Jerusalem Winter School on the subject of dark matter. Tsvi Piran was the very able scientific coordinator. The refereed and edited versions of those pedagogical lectures were published, together with a few relevant reprints, in 1988 by World Scientific Publications as "Dark Matter in the Universe," with J. N. Bahcall, T. Piran, and S. Weinberg as editors. Most of the lectures of that School are reproduced here together with a review article that appears as the last chapter in this book and which summarizes succinctly the state of dark matter research in 2004.

The lectures presented in 1986 represent a solid introduction to the field of dark matter studies (and incidentally to a number of other currently hot topics in astrophysics) and will enable a graduate student or researcher in astronomy or physics to read with understanding the contemporary research papers in the subject. Most of what we have learned since 1986is what the dark matter is not; discovering what the dark matter really is remains an exciting challenge.

The lectures and the reprints reproduced in this book have some special advantages for the student and for the active researcher. First of all, the style of the lectures is pedagogical and detailed. This makes it easier to understand the arguments and the assumptions that underlie the conclusions. Second, much of the basic research on dark matter was fresh at the time these lectures were presented and therefore the reader will see the way people participating in these first analyses thought about the puzzles and the challenges. Often, first-look approaches are easier to understand than the more polished presentations that come afterwards.

Of course, much important work has been done in the almost two decades since the Jerusalem Dark Matter Winter School was held. I have resisted the temptation to try to provide a list of references that would cover the more recent literature. It would a very long list indeed and any given reader would only be interested in a small fraction of the newer literature. Today, there are excellent tools available on the Web so that anyone can find articles that cite earlier articles, like the ones that are cited in the lectures reproduced here. These Web based applications have the advantage of being both convenient and continuously updated.

The most important progress in understanding the astronomical role of dark matter since the 1986 Winter School has been in the context of the formation of large scale structure in the universe and of galaxy formation. The concluding chapter of this book is new; all of the other chapters appeared in the previous edition. The new final chapter, by A. Aguirre, summarizes the current theoretical ideas, the existing observational results, and the future challenges for the very successful cosmological scenario based upon the hypothesis of Cold Dark Matter.

I have chosen to omit from this edition the lectures that I gave at the Winter School on the topic of dark matter in the Disk of our Galaxy. The mathematical techniques described in the omitted lectures have been used by J. Holmberg and C. Flynn (see MNRAS, **313**, 209 (2000) and astro-ph/0405155) to show, using recent Hipparcos observations that are a great improvement over earlier data, that there is no appreciable amount of dark matter in the Galactic Disk. There is a lesson in this development which is useful for all students (and researchers) of astronomy and astrophysics: theoretical inferences are–at best–no better than the observations on which they are based.

Contents of This Book

Chapter 2 of this book is a reprint of a prototypical study of the dark matter in the galaxy NGC 3198, of the kind carried out so fruitfully and systematically by Vera Rubin and her colleagues. The extensive observational data available for this galaxy made possible a detailed analysis that illustrates clearly the astronomical context and the general nature of dark mater in galaxies. This observational paper, by T. S. Van Albada and colleagues, symbolizes that the fact that Nature forced us to acknowledge dark matter without the slightest *a priori* theoretical motivation for its existence. Chapter 3, by J. N. Bahcall and S. Casertano, describes one of the most persistent puzzling aspects of dark matter. There is a conspiracy between dark matter and luminous matter to arrange themselves so that the transition in a galaxy from domination by dark matter to domination by luminous matter produces no easily observable features. The reader can see the conspiracy at work in the measurements reported in Chapter 2 for NGC 3198.

Chapter 4, by J. P. Ostriker and C. Thompson, discusses the evolution of globular clusters, systems of typically 10^5 stars. This chapter exposes the reader to some of the classical stellar dynamical questions and techniques that are useful in treating the equilibrium and the evolution of large numbers of stars. The concluding section of this chapter considers the possibility that massive black holes are a significant component of the dark matter in the halos of galaxies like NGC 3198. Chapte 5, also by Ostriker and Thompson, describes in pedagogical detail the effects of positive-energy perturbations in an expanding universe. The authors have in mind perturbations from a galaxy undergoing a burst of star formation, an active quasar, or even a superconducting cosmic string. For the student or researcher interested in astrophysical problems, the most valuable aspect of this chapter is that it describes in an accessible way the "dirty details" of the subject, including hydrodynamics in an expanding universe, shock waves, instabilities, and the influence of dark matter.

Chapter 6, by Scott Tremaine and Hyung Mok Lee, is a concise and accessible introduction to the entire subject of dark matter in galaxies and clusters of galaxies. If you read this pedagogically presented collection of five lectures and verify the equations, then you will be will equipped to do research in the subject. In fact, this chapter is a self-contained summary of the tools needed to address many problems in modern astrophysics. Separate sections are devoted to an overview of the subject of dark matter, the theory of stellar dynamics, the cores of elliptical galaxies and dwarf spheroidal galaxies, the Halo of the Milky Way Galaxy, binary galaxies, and masses of groups and clusters of galaxies. Imagine you were a graduate student in a university where there was no active research in astrophysics. In this case, Chapter 6 would be just what you needed. You could easily find a number of interesting and important topics for a graduate thesis by studying this chapter and then applying the techniques described by Tremaine and Lee to new data sets, data sets that are much more extensive than those that were available in 1986. In fact, Chapter 6 is written so clearly and logically that the uninitiated and the expert can both benefit greatly by studying the material systematically.

The ideal way to study dark matter is, in many contexts, by gravitational lensing. Lensing measures the total amount of matter independent of the light that the matter emits. This is just what we want in order to study dark matter. Chapter 7, by R. D. Blandford and C. S. Kochanek, presents an exceptionally clear introduction to the theory and practice of gravitational lensing. The subject has grown enormously since these lectures were given but the principles have not changed. You can find in the lectures everything you need to know to read with understanding the multitude of current papers on gravitational lensing. The topics covered include order of magnitude estimates, the different formalisms for describing gravitational lensing and a comparison of their relative advantages, results for a variety of special cases, generic features of the images, an unusually clear discussion of caustics and catastrophe theory, and compound lenses. Every serious student of dark matter should read this chapter carefully.

Chapters 8-10, by W. H. Press and D. N. Spergel, cover in an introductory but mathematically explicit style three important subjects: inflationary cosmology, cosmic strings, and WIMPS in the Sun and in the laboratory. The lectures are characterized by their directness; the student is given succinct physical arguments followed by the corresponding mathematical equations that in each case summarize the essence of the topic. If you never heard before of inflation or cosmic strings or WIMPS, you could learn what you need to know to be an intelligent consumer of the modern literature on these subjects by reading the introductions in Chapters 8-10. You can't go to a contemporary conference on cosmology without hearing about inflation and you can't go to a contemporary conference on the physics of dark matter without hearing about WIMPS. Although important details have changed since these lectures were written, the basic principles outlined by Press and Spergel are valid today. There is less current interest in cosmic strings today than there was in 1986, largely because they have not been observed, but the subject is still relevant for cosmological investigations.

Nearly all physicists and astronomers assume that dark matter is real. But in the 19th century, nearly all physicists assumed that the aether was real. Consensus does not guarantee correctness. In Chapter 11, Mordehai Milgrom presents a non-relativistic description, usually referred to as MOND, in which the phenomena that are conventionally ascribed to dark matter are instead explained by the failure of Newtonian gravitation at a very low acceleration. This mathematical model makes a number of remarkable predictions. The most remarkable of all the predictions is that every rotation curve of an isolated spiral galaxy can be obtained from the distribution of observed baryonic material using only one parameter (the mass to light ratio). Only a small number of measured rotation curves were available when this prediction was first made in 1983, but today many hundreds of rotation curves are known with good accuracy. If there are any exceptions to the prediction, for the rotation curves of isolated galaxies, of the modified Newtonian dynamics advocated by Milgrom, then they are rare. This is an extraordinary situation. If the usual dark matter picture is correct, then there is no reason why rotation curves measured in different galaxies should not have large random differences. A conspiracy of the kind described in Chapter 3 is required to suppress variety and to hide the signature of dark matter in galactic rotation curves. Something deep is right about MOND, if only in the sense that the formalism describes in a succinct way a number of *a priori* surprising regularities in the data for galactic systems. Everyone interested in dark matter should read Chapter 11 and think about its implications.

The concluding Chapter 12 by Anthony Aguirre presents the theoretical basis for understanding the role of Cold Dark Matter in determining the observed anisotropies of the Cosmic Microwave Background, the power spectra of the Ly-α forest, and the distribution of galaxies. Aguirre also clearly and succinctly summarizes the theoretical ideas and the observational data related to the formation of galaxies and their halos. In the concluding section of this chapter, Aguirre steps back and outlines objectively and insightfully the current status of galaxy formation theory, as well as the outstanding challenges to the hypothesis of Cold Dark Matter. Everyone interested in modern cosmology can benefit from reading this chapter.

May 2004