Visible and Dark Matter in the Universe

This is a concise introduction to modern astrophysics for physicists, with a focus on galaxy dynamics and the discovery of dark matter halos in galaxies. Part I summarizes important discoveries in observational astronomy and astrophysics, in a manner accessible to those who are new to the topic. Building on this foundation, Part II describes the study of dark matter and provides more detail on galactic dynamics. Important physical concepts that form the basis of key astrophysical phenomena are explained, avoiding unnecessary technicalities and complex derivations. The approach is semi-empirical and emphasizes the importance of key measurements and observations in formulating fundamental theoretical questions and developing their solutions. Students are encouraged to develop a deep understanding of major discoveries and contemporary research topics, beyond the simple application of practical models and formulae, as a bridge to more advanced study in astrophysics.

GIUSEPPE BERTIN is Professor of Physics at the University of Milan, Italy. He has previously held several positions at the Scuola Normale Superiore and the Massachusetts Institute of Technology, and has been a member of the Kavli Institute for Theoretical Physics, University of California, Santa Barbara. His previous books include *Spiral Structure in Galaxies: A Density Wave Theory* with C. C. Lin (MIT Press) and *Dynamics of Galaxies* (Cambridge University Press). He was elected to Italy's Accademia Nazionale dei Lincei in 2013, when he received its Premio Nazionale del Presidente della Repubblica in Science.

Visible and Dark Matter in the Universe

A Short Primer on Astrophysical Dynamics

GIUSEPPE BERTIN
University of Milan

CAMBRIDGE
UNIVERSITY PRESS

CAMBRIDGE
UNIVERSITY PRESS

Shaftesbury Road, Cambridge CB2 8EA, United Kingdom

One Liberty Plaza, 20th Floor, New York, NY 10006, USA

477 Williamstown Road, Port Melbourne, VIC 3207, Australia

314–321, 3rd Floor, Plot 3, Splendor Forum, Jasola District Centre,
New Delhi – 110025, India

103 Penang Road, #05–06/07, Visioncrest Commercial, Singapore 238467

Cambridge University Press is part of Cambridge University Press & Assessment,
a department of the University of Cambridge.

We share the University's mission to contribute to society through the pursuit of
education, learning and research at the highest international levels of excellence.

www.cambridge.org
Information on this title: www.cambridge.org/9781316519318

DOI: 10.1017/9781009023368

First published 2023

A catalogue record for this publication is available from the British Library.

*A Cataloging-in-Publication data record for this book is available from the
Library of Congress*

ISBN 978-1-316-51931-8 Hardback

Additional resources for this publication at www.cambridge.org/bertin

To my brother Alberto, a physics teacher with great
interest in science and astronomy

Contents

	Preface		*page* xi
	Acknowledgments		xiv
	PART I	Visible Matter	1
1	**Light**		3
	1.1	The Electromagnetic Spectrum, Imaging, and Spectroscopy	4
	1.2	Apparent and Intrinsic Quantities, Standard Rods, and Standard Candles	10
	1.3	Emission from Complex Sources and Mass-to-Light Ratios	16
	1.4	Dynamical Measurement of the Distance to a Globular Cluster	19
2	**Optical Astronomy**		22
	2.1	The Hubble Deep Fields	24
	2.2	Distant Supernovae and the Acceleration of the Universe	26
	2.3	Astrometry: From *Hipparcos* to *Gaia*	29
	2.4	Lagrangian Points of the Sun–Earth System as Optimal Sites	29
3	**Radio Astronomy**		37
	3.1	The 21-cm Neutral-Hydrogen Line	38
	3.2	Cosmic Microwave Background	39
	3.3	Pulsars	42
	3.4	Quasars and Gravitational Lensing	45
	3.5	Rotating Systems	49
4	**X-Ray and Gamma Ray Astronomy**		54
	4.1	X-Ray Binaries	56
	4.2	Diffuse Emission from Clusters of Galaxies	57

Cambridge University Press & Assessment
978-1-316-51931-8 — Visible and Dark Matter in the Universe
Giuseppe Bertin
Frontmatter
More Information

4.3 Gamma Ray Bursts 59
4.4 Fluid Models 61

5 Astroparticle Physics, Gravitational Waves, and Space Physics 67
5.1 The Solar Neutrino Problem 71
5.2 Direct Detection of Gravitational Waves 74
5.3 The Solar Wind as a Collisionless Plasma 75
5.4 Gravity Assists and Other Curiosities 76

PART II Dark Matter 81

6 Galaxies 83
6.1 The Discovery of Galaxies and Their Morphological Classification 85
6.2 Scales 91
6.3 Structure and Kinematics of Spiral Galaxies 96
6.4 The Virial Theorem for a Self-Gravitating System 98

7 The Supermassive Black Hole at the Center of the Milky Way 106
7.1 The Dynamical Paradigm at the Basis of the "Discovery" of Invisible Mass 107
7.2 Early Evidence for a Supermassive Black Hole at the Galactic Center 108
7.3 The Orbit of the Star S2 around SgrA* 109
7.4 Supermassive Black Holes in Other Galaxies 112
7.5 Ellipses as Closed Orbits in Different Potentials 113

8 Two Precursors of the Problem of Dark Matter 119
8.1 Clusters of Galaxies 119
8.2 The Thickness of the Galactic Disk in the Solar Neighborhood 125
8.3 The Isothermal Self-Gravitating Slab 128

9 The Discovery of Dark Halos around Spiral Galaxies 132
9.1 Flat Rotation Curves 135
9.2 Decomposition of an Observed Rotation Curve 141
9.3 Self-Consistent Decomposition 145
9.4 Dynamical Arguments 147

10 The Cosmological Context 151
10.1 Dark Matter Halos in Elliptical Galaxies 152
10.2 Impact of Galaxy Halos on the Cosmological Density Parameter 157

10.3 Numerical Simulations of Structure Formation in the Universe 159
10.4 *Gaia* Studies of the Near Universe 162
10.5 Dark Matter in Globular Clusters? 163
10.6 Lensing Studies of Dark Matter in the Distant Universe 165
10.7 An Alternative to Dark Matter 167

Index 173

Preface

The structure of this book reflects the first part of a one-semester course addressed to third-year undergraduate students of physics at the University of Milan. In the form taken in the last 15 years, the course contained two additional parts. The second part was taught by a colleague active in the study of the cosmic microwave background radiation, who introduced several aspects of observational astronomy and observational cosmology (recently this contribution was replaced by two colleagues briefly covering the topics of black holes in astrophysics and modern aspects of cosmology). The third part was given by a colleague working on neutrino experiments at Gran Sasso, who focused on topics in astroparticle physics.

My task was to set the general themes for such a composite set of lectures, which were meant to help undergraduate students, with no previous experience in astronomy courses, to become familiar with key research topics in astrophysics and possibly to decide, on the basis of these lectures, whether they would wish to undertake a program in astrophysics for their future graduate studies.

Within this general framework, in my part (20 hours of class) I tried to pose and answer the following key questions:

(i) What are the most significant discoveries in astrophysics of the last 100 years?
(ii) What does research in astrophysics consist in?
(iii) Why does gravity, even at the classical level, still pose some of the most intriguing and challenging problems in modern astrophysics?

To proceed, and to do so at an elementary level within a very limited number of classes, I decided to focus on few selected topics that I judged to be particularly significant and instructive. I divided my time-slot in two equal parts. The first was devoted to providing highlights of major discoveries, as an answer to the first key question mentioned above. Then, in order to be more specific and to tackle at least one topic in some depth, in the second part of my slot I described the discovery of dark matter from the study of galaxies and clusters of galaxies. This allowed me to provide an answer to the third key question posed above. I thus produced a personal view of introducing astrophysics to students of physics. My classes were all based on concrete examples, in which I tried to convey my firm conviction that progress and inspiration come from few decisive measurements/observations rather than from abstract or deductive arguments.

The interactions with the students revealed a number of apparently surprising characteristics of our physics program. While generally showing a rather satisfactory background in modern physics (in particular, many already showed a reasonable familiarity with basic concepts in quantum mechanics and general relativity), the students often, almost always, exhibited a rather weak and naive attitude toward classical mechanics and related tools of calculus. Given the fact that my research activity focuses on the dynamics of galaxies and other stellar systems, I thus found it natural to take the task of presenting a short introduction to astrophysics as an excuse to insert, here and there, essentially in each class I gave, some simple problems or a brief outline of some basic concepts in classical mechanics. (In general, this supplementary material corresponds to the final section of each chapter.) In doing so, I tried to prompt the students to catch up with topics that not too long ago would be taken for granted as first-year physics. These digressions in classical mechanics not only turned out to be useful, but also helped excite some interest in dynamical aspects of astrophysics. In other words, to some students they may have shown that a view of astrophysics from the dynamical window has its own beauty.

For obvious reasons, the 10 chapters of this book expand significantly what I could teach realistically in 10 two-hour classes, and thus this text may be taken as the basis for a full one-term course.

I should also mention that some of the topics covered in this short book draw from material to some extent present in two books that I wrote. However, there is a clear contrast in emphasis and content, which here are fully aimed at communicating with undergraduate students that are imagined to meet astronomy and astrophysics for the first time. In turn, the book *Dynamics of Galaxies* (2nd ed., Cambridge University Press, 2014) is addressed to graduate students, with the goal of providing a coherent framework for our current perception and tools of investigation on the subject of the dynamics of galaxies, while the monograph *Spiral Structure in Galaxies: A Density Wave Theory* (co-authored with C. C. Lin; MIT Press, 1996) has a specific objective, that is, to provide a coherent framework for understanding spiral structure in galaxies.

Of course, in class I make wide use of the blackboard and plots taken from books and other published material. In the current text, there are only a few figures, most of them taken from seminal publications. My hope is that this apparent limitation could serve as an incentive for the student to look up the original references and other sources so as to properly complement the text with the material that is generally provided in class. I am especially keen on encouraging students to look up original references, which are selected and listed in the relevant endnotes.

Finally, I would like to mention another point that is complementary to the role of my teaching in writing this book. In Milan, at the end of their third year, undergraduate students write an essay (in Italian, *Tesi di Laurea Triennale*), for which the student has no obligation of obtaining original results as would be suitable for a scientific publication or for a Ph.D. thesis. For the students, the essay is a way to get exposed, often for the first time, to scientific research; that is, to get an answer to the second key question that I raised above. So far I have supervised about 20 such projects on topics of astrophysical interest. The interactions with students during the supervision process have had a significant influence in determining the content and the structure of the present book.

Cambridge University Press & Assessment
978-1-316-51931-8 — Visible and Dark Matter in the Universe
Giuseppe Bertin
Frontmatter
More Information

Acknowledgments

It would be impossible to thank properly all the scientists who have contributed to the ideas and the results presented here. The Department of Physics, University of Pisa, is thanked for their hospitality, which has given me the opportunity to write part of this book.