

THE DARK MATTER PROBLEM

A Historical Perspective

Most astronomers and physicists now believe that the matter content of the Universe is dominated by dark matter: hypothetical particles which interact with normal matter primarily through the force of gravity. Though invisible to current direct detection methods, dark matter can explain a variety of astronomical observations. This book describes how this theory has developed over the past 75 years, and why it is now a central feature of extragalactic astronomy and cosmology.

Current attempts to directly detect dark matter locally are discussed, together with the implications for particle physics. The author comments on the sociology of these developments, demonstrating how and why scientists work and interact. Modified Newtonian Dynamics (MOND), the leading alternative to this theory, is also presented.

This fascinating overview will interest cosmologists, astronomers, and particle physicists. Mathematics is kept to a minimum, so the book can be understood by non-specialists.

ROBERT H. SANDERS is Professor Emeritus at the Kapteyn Astronomical Institute, Groningen, the Netherlands. He has worked in the field of dark matter for many years.

THE DARK MATTER PROBLEM

A Historical Perspective

ROBERT H. SANDERS

Kapteyn Astronomical Institute, Groningen



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/9780521113014

© R. Sanders 2010

This publication is in copyright. Subject to statutory exception and to the provisions
 of relevant collective licensing agreements, no reproduction of any part may take
 place without the written permission of Cambridge University Press & Assessment.

First published 2010

First paperback edition 2013

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

Library of Congress Cataloging-in-Publication data

Sanders, Robert H.

The dark matter problem : a historical perspective / Robert H. Sanders.

p. cm.

Includes bibliographical references and index.

ISBN 978-0-521-11301-4

1. Dark matter (Astronomy)—History. I. Title.

QB791.3.S25 2010

523.1'126—dc22

2010004532

ISBN 978-0-521-11301-4 Hardback

ISBN 978-1-107-67718-0 Paperback

Cambridge University Press & Assessment has no responsibility for the persistence
 or accuracy of URLs for external or third-party internet websites referred to in this
 publication and does not guarantee that any content on such websites is, or will
 remain, accurate or appropriate.

Contents

	<i>Acknowledgements</i>	<i>page vii</i>
1	Introduction	1
2	Early history of the dark matter hypothesis	11
2.1	Prehistory	11
2.2	Zwicky and the modern concept of dark matter	12
2.3	Dark matter on galaxy scales	15
2.4	Radio astronomy: a new tool for galactic astronomy	20
2.5	Finzi sums it up	23
3	The stability of disk galaxies: the dark-halo solution	26
3.1	Building disk galaxies: too hot to be real	26
3.2	Dark halos to the rescue	30
3.3	Larger implications	34
4	Direct evidence: extended rotation curves of spiral galaxies	38
4.1	Radio telescopes: single-dish and interferometers	38
4.2	Early results of single-dish neutral hydrogen observations	44
4.3	Early observations of spiral galaxies with radio interferometers	48
4.4	Flat rotation curves: perception approaches reality	51
5	The maximum-disk: light traces mass	57
5.1	Reaction follows revolution	57
5.2	The anomaly exists beyond the visible disk	62
5.3	Low-surface-brightness galaxies and sub-maximal disks	65
5.4	Reflections on observations of rotation curves	67
6	Cosmology and the birth of astroparticle physics	69
6.1	A brief history of modern cosmological models	69
6.2	Structure formation: dark matter again to the rescue	72
6.3	Some like it hot, most like it cold, all like it in the pot 10 billion years old	76

vi	<i>Contents</i>	
6.4	What is the matter?	80
6.5	A new paradigm: standard CDM	84
7	Clusters revisited: missing mass found	87
7.1	The reality of the cluster discrepancy	87
7.2	Hot gas in clusters of galaxies	88
7.3	Gravitational lensing: a new method for probing cluster mass distribution	93
7.4	The Bullet	98
8	CDM confronts galaxy rotation curves	101
8.1	What do rotation curves require of dark matter?	101
8.2	Global scaling relations	105
8.3	Structure formation in a CDM universe	106
8.4	The mass distribution in CDM dark halos	109
8.5	Substructure in CDM halos	113
8.6	The Tully–Fisher law	115
8.7	Can CDM be falsified by galaxy phenomenology?	117
9	The new cosmology: introducing dark energy	119
9.1	The accelerated expansion of the Universe	119
9.2	COBE finds the primordial fluctuations	124
9.3	What do we see in the CMB?	125
9.4	Boomerang to WMAP: the age of precision cosmology	127
9.5	Reflections	130
10	An alternative to dark matter: modified Newtonian dynamics	132
10.1	Naive modifications of Newtonian attraction	132
10.2	MOND	133
10.3	MOND and hot galaxies	138
10.4	MOND and rotation curves	140
10.5	The problem of clusters	143
10.6	Relativistic MOND: TeVeS	144
10.7	Summing up: MOND vs. dark matter	147
11	Seeing dark matter: the theory and practice of detection	150
11.1	Non-gravitational detection of dark matter	150
11.2	The practice of direct detection	152
11.3	Indirect detection of dark matter	159
11.4	Light on dark matter: the story so far	165
12	Reflections: a personal point of view	166
	<i>Appendix Astronomy made simple</i>	173
	<i>References</i>	195
	<i>Index</i>	202

Acknowledgements

The task of describing the historical development of the dark matter problem would have been much more difficult without the assistance of a number of colleagues and old friends. In the first place I thank Mort Roberts for numerous conversations and emails on the events surrounding the early observations of spiral-galaxy rotation curves. The insights of such a major participant in these developments have been a treasure house, although I hasten to add that the conclusions drawn here from these insights (particularly concerning matters of priority) have been entirely my own.

Throughout the years I have benefited from uncountable conversations with my Groningen colleagues, Renzo Sancisi and Tjeerd van Albada, on the interpretation of the observations of rotation curves. I deeply value this contact, and their numerous useful suggestions contributed both to the content and presentation of this book. I have also benefited enormously from collaborations with generations of Groningen students: Kor Begeman, Adrick Broeils, Marc Verheijen, Edo Noordermeer, and Rob Swaters. We have spent many hours together looking at and discussing rotation curves of galaxies ranging from faint dwarfs (barely a smudge on the photographic plate) to those of giant luminous spiral systems. Altogether, in their objective and critical way, they have formed my view of the phenomenology.

There is nothing like a discussion with a critical but well-meaning colleague and friend to clarify ideas and sharpen arguments. In this regard I am very grateful to Jacqueline van Gorkom for chats about the sociology of rotation-curve observers and the philosophy of science. I also thank Rien van de Weygaert and Saleem Zaroubi for attempting to fill in the many gaps in my knowledge of cosmology and structure formation, particularly with respect to the historical developments in this field.

Moti Milgrom and Stacy McGaugh have commented on several of the chapters here, and, as always, their remarks are perceptive and helpful. For me it

has been a special privilege to have known and worked with Moti, Stacy and Jacob Bekenstein during the past quarter-century; they are creative and bold scientists.

I would like to thank Vince Higgs and his colleagues at Cambridge University Press for their constant help and many useful suggestions.

Further I am very grateful to Stefano Casertano, Jacob Bekenstein, and especially the French translator, Benoit Clenet, for pointing out embarrassingly many omissions, ambiguities and errors in the first printing of this book.

Finally, I thank my wife, Christine, for her patience and for coming to terms with our different dreams of retirement.