# ASTROPHYSICS OF PLANET FORMATION

The study of planet formation has been revolutionized by recent observational breakthroughs, which have allowed the detection and characterization of extrasolar planets, the imaging of protoplanetary disks, and the discovery of the Solar System's Kuiper Belt.

Written for beginning graduate students, this textbook provides a basic understanding of the astrophysical processes that shape the formation of planetary systems. It begins by describing the structure and evolution of protoplanetary disks, moves on to the formation of planetesimals, terrestrial and gas giant planets, and concludes by surveying new theoretical ideas for the early evolution of planetary systems.

Covering all phases of planet formation – from protoplanetary disks to the dynamical evolution of planetary systems – this introduction can be understood by readers with backgrounds in planetary science, and observational and theoretical astronomy. It highlights the physical principles underlying planet formation and the areas where more research and new observations are needed.

PHILIP J. ARMITAGE is a Professor in the Department of Astrophysical and Planetary Sciences at the University of Colorado, Boulder, and a Fellow of JILA. His research focuses on theoretical and computational studies of protoplanetary disks, planet formation, and black hole astrophysics. He has extensive teaching experience at the advanced undergraduate and graduate level.

# ASTROPHYSICS OF PLANET FORMATION

PHILIP J. ARMITAGE
*University of Colorado, Boulder*

CAMBRIDGE
UNIVERSITY PRESS

CAMBRIDGE UNIVERSITY PRESS
Cambridge, New York, Melbourne, Madrid, Cape Town, Singapore, São Paulo, Delhi

Cambridge University Press
The Edinburgh Building, Cambridge CB2 8RU, UK

Published in the United States of America by Cambridge University Press, New York

www.cambridge.org
Information on this title: www.cambridge.org/9780521887458



First published 2010

Printed in the United Kingdom at the University Press, Cambridge

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

*Library of Congress Cataloguing in Publication data*
Armitage, Philip J., 1971–
Astrophysics of planet formation / Philip Armitage.
p. cm.
ISBN 978-0-521-88745-8 (hardback)
1. Planets – Origin. 2. Astrophysics. I. Title.
QB603.O74A76 2010
523.4 – dc22 2009036992

ISBN 978-0-521-88745-8 Hardback

# Contents

# Preface

The study of planet formation has a long history. The idea that the Solar System formed from a rotating disk of gas and dust – the *Nebula Hypothesis* – dates back to the writings of Kant, Laplace, and others in the eighteenth century. A quantitative description of terrestrial planet formation was already in place by the late 1960s, when Viktor Safronov published his now classic monograph *Evolution of the Protoplanetary Cloud and Formation of the Earth and the Planets*, while the main elements of the core accretion theory for gas giant planet formation were developed in the early 1980s. More recently, a wealth of new observations has led to renewed interest in the problem. The most dramatic development has been the identification of extrasolar planets, first around a pulsar and subsequently in large numbers around main-sequence stars. These detections have furnished a glimpse of the Solar System's place amid an extraordinary diversity of extrasolar planetary systems. The advent of high resolution imaging of protoplanetary disks and the discovery of the Solar System's Kuiper Belt have been almost as influential in focusing theoretical attention on the initial conditions for planet formation and the role of dynamics in the early evolution of planetary systems.

My goals in writing this text are to provide a concise introduction to the classical theory of planet formation and to more recent developments spurred by new observations. Inevitably, the range of topics covered is far from comprehensive. The emphasis is firmly on the *astrophysical* aspects of planet formation, including the physics of the protoplanetary disk, the agglomeration of dust into planetesimals and planets, and the dynamical interactions between those bodies and the disk and between themselves. Planets are made of rock, ice, and gas, but the information that can be deduced from study of the chemical and geological make-up of those materials – the subject of *cosmochemistry* and much of traditional planetary science – is mostly ignored.

This book is an outgrowth of a graduate course that I teach at the University of Colorado in Boulder, for which the prerequisites are undergraduate classical physics and elementary mathematical methods. The primary readership is beginning graduate students, but most of the text ought to be accessible to undergraduates who have had some exposure to Newtonian mechanics and fluid dynamics. For the more sophisticated reader there is nothing here that is new, though the tone of the presentation – and in particular the emphasis on the coupling between turbulent processes in the disk and planet formation – focuses on what I consider to be important modern developments to a greater extent than older reviews. Despite recent progress one cannot disguise the fact that several critical problems in planet formation – foremost among them the nature of angular momentum transport within the protoplanetary disk and the formation mechanism of planetesimals – remain unsolved, and I have given extensive references to the technical literature to enable interested readers to explore these and other controversial topics further.

A number of colleagues have helped out in the preparation of this book. The discussion of the internal structure of the Solar System's gas giants draws heavily on the work of Tristan Guillot, who generously provided figures illustrating constraints on the core masses of Jupiter and Saturn. Keiji Ohtsuki was kind enough to provide figures showing the velocity evolution of planetesimals, while Sean Raymond prepared new figures depicting the late stages of terrestrial planet formation. My thanks also to Richard Alexander, Eric Feigelson, Dave Stevenson, Michele Trenti, Dimitri Veras, and Jared Workman, who shared their expertise on different topics and gave many of the chapters a critical reading.

Parts of the book were completed during a stay at UCLA, and I warmly thank Andrea Ghez and her colleagues in the Physics and Astronomy Department for their hospitality.