It is just over ten years since the first planet outside our Solar System was detected. Since then, much work has been done to try to understand how extrasolar planets may form. This volume addresses fundamental questions concerning the formation of planetary systems in general, and of our Solar System in particular. Drawing from recent advances in observational, experimental, and theoretical research, it summarizes our current understanding of the planet formation processes, and addresses major open questions and research issues. Chapters are written by leading experts in the field of planet formation and extrasolar planet studies. The book is based on a meeting held in 2004 at Ringberg Castle in Bavaria, where experts gathered together to present and exchange their ideas and findings. It is a comprehensive resource for graduate students and researchers, and is written to be accessible to newcomers to the field.

The Cambridge Astrobiology series aims to facilitate the communication of recent advances in astrobiology, and to foster the development of scientists conversant in the wide array of disciplines needed to carry astrobiology forward. Books in the series are at a level suitable for graduate students and researchers, and are written to be accessible to scientists working outside the specific area covered by the book.

Hubert Klahr and Wolfgang Brandner are both at the Max-Planck-Institute for Astronomy in Heidelberg. Hubert Klahr is Head of the Theory Group for Planet and Star Formation, and Wolfgang Brandner is a staff researcher and Head of the Adaptive Optics Lab.
Cambridge Astrobiology

Series Editors
Bruce Jakosky, Alan Boss, Frances Westall, Daniel Prieur, and Charles Cockell

Books in the series:
1. Planet Formation: Theory, Observations, and Experiments
   Edited by Hubert Klahr and Wolfgang Brandner
   ISBN-10 0-521-86015-6
PLANET FORMATION

Theory, Observations, and Experiments

Edited by

HUBERT KLAHR
Max-Planck-Institut für Astronomie, Heidelberg, Germany

WOLFGANG BRANDNER
Max-Planck-Institut für Astronomie, Heidelberg, Germany
Dedicated to the one and only true planet formation specialist
Slartibartfast of Magrathea and his father D. N. Adams.
## Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preface</td>
<td>xiii</td>
</tr>
<tr>
<td>Acknowledgments</td>
<td>xv</td>
</tr>
<tr>
<td>1 Historical notes on planet formation</td>
<td>1</td>
</tr>
<tr>
<td>Peter Bodenheimer</td>
<td></td>
</tr>
<tr>
<td>1.1 Introduction</td>
<td>1</td>
</tr>
<tr>
<td>1.2 Descartes and von Weizsäcker: vortices</td>
<td>1</td>
</tr>
<tr>
<td>1.3 Magnetic effects</td>
<td>2</td>
</tr>
<tr>
<td>1.4 Gravitational instability</td>
<td>3</td>
</tr>
<tr>
<td>1.5 Core accretion: gas capture</td>
<td>6</td>
</tr>
<tr>
<td>1.6 Planet searches</td>
<td>8</td>
</tr>
<tr>
<td>2 The Formation and Evolution of Planetary Systems: placing our Solar System in context</td>
<td>14</td>
</tr>
<tr>
<td>Jeroen Bouwman, Michael R. Meyer, Jinyoung Serena Kim, Murray D. Silverstone, John M. Carpenter, and Dean C. Hines</td>
<td></td>
</tr>
<tr>
<td>2.1 Introduction</td>
<td>14</td>
</tr>
<tr>
<td>2.1.1 The formation of planets: from protoplanetary towards debris disk systems</td>
<td>16</td>
</tr>
<tr>
<td>2.1.2 The Spitzer Space Telescope and the formation and evolution of planetary systems legacy program</td>
<td>17</td>
</tr>
<tr>
<td>2.2 From protoplanetary to debris disks: processing and dispersion of the inner dust disk</td>
<td>20</td>
</tr>
<tr>
<td>2.3 Debris disks: Asteroid or Kuiper Belt?</td>
<td>25</td>
</tr>
<tr>
<td>3 Destruction of protoplanetary disks by photoevaporation</td>
<td>31</td>
</tr>
<tr>
<td>Sabine Richling, David Hollenbach and Harold W. Yorke</td>
<td></td>
</tr>
<tr>
<td>3.1 Introduction</td>
<td>31</td>
</tr>
<tr>
<td>3.2 Photoevaporation and other dispersal mechanisms</td>
<td>33</td>
</tr>
<tr>
<td>3.3 Photoevaporation by external radiation</td>
<td>34</td>
</tr>
<tr>
<td>3.4 Photoevaporation by the central star</td>
<td>36</td>
</tr>
</tbody>
</table>
### Contents

3.5 Photoevaporation and dust evolution 39  
3.6 Conclusions 40  
Acknowledgments 41  

4 Turbulence in protoplanetary accretion disks: driving mechanisms and role in planet formation  
*Hubert Klahr, Michal Różycka, Natalia Dziourkevitch, Richard Wünsch, and Anders Johansen*  
4.1 Introduction 42  
4.1.1 Protostellar collapse and formation of disks 42  
4.1.2 Observations of accretion in protoplanetary systems 43  
4.1.3 Self-gravity and the early evolution of disks 44  
4.1.4 Viscous evolution 46  
4.2 Magnetohydrodynamic turbulence 47  
4.2.1 Non-ideal magnetohydrodynamics 48  
4.2.2 Ohmic dissipation 50  
4.2.3 Ambipolar diffusion 50  
4.2.4 Hall term 50  
4.3 Layered accretion 51  
4.3.1 Ionization structure 52  
4.3.2 Layered disk evolution 55  
4.4 Alternative instabilities in the dead zone 56  
4.5 Transport by turbulence 57  
4.5.1 Dust dynamics 58  
4.5.2 Dust-trapping mechanisms 59  
4.5.3 Turbulent diffusion 61  
4.6 Conclusions 62  

5 The origin of solids in the early Solar System  
*Mario Trieloff and Herbert Palme*  
5.1 Introduction: geoscience meets astronomy 64  
5.2 Meteorites: remnants of planetesimal formation 4.6 billion years ago in the asteroid belt 66  
5.3 Calcium-aluminum-rich inclusions and chondrules: remnants from the earliest Solar System 67  
5.4 Compositional variety of chondrites: planetesimal formation occurred at a variety of conditions in the protoplanetary disk 69  
5.4.1 Metal abundance and oxidation state 69  
5.4.2 Ratio of refractory to volatile elements 73  
5.4.3 Major element fractionations: Mg, Si, Fe 74  
5.4.4 Oxygen isotopes 74
5.5 Isotopic homogeneity of Solar-System materials 75
  5.5.1 Heterogeneity inherited from the interstellar medium: restricted to rare individual grains 76
  5.5.2 Heterogeneous or homogeneous distribution of short-lived nuclides: mixed evidence 77
5.6 Dating accretion, heating, and cooling of planetesimals 78
5.7 A timescale of early Solar-System events 80
5.8 Formation of terrestrial planets 83
5.9 Disk dissipation, Jupiter formation and gas–solid fractionation 84
5.10 Summary 86
Acknowledgments 89

6 Experiments on planetesimal formation
  Gerhard Wurm and Jürgen Blum 90
  6.1 Introduction 90
  6.2 Two-body collisions and the growth of aggregates in dust clouds 91
    6.2.1 Hit-and-stick collisions 91
    6.2.2 Medium/high kinetic-energy collisions 100
  6.3 Dust aggregate collisions and electromagnetic forces 106
  6.4 Dust aggregate collisions and dust–gas interactions 107
  6.5 Future experiments 108
  6.6 Summary 109
  Acknowledgments 111

7 Dust coagulation in protoplanetary disks
  Thomas Henning, Cornelis P. Dullemond, Sebastian Wolf, and Carsten Dominik 112
  7.1 Introduction 112
  7.2 Observational evidence for grain growth 113
  7.3 Radiative transfer analysis 116
  7.4 Theoretical models of dust coagulation 118
    7.4.1 Important processes 118
    7.4.2 Global models of grain sedimentation and aggregation in protoplanetary disks 124
  7.5 Summary 128

8 The accretion of giant planet cores
  Edward W. Thommes and Martin J. Duncan 129
  8.1 Introduction 129
  8.2 Estimating the growth rate 131
    8.2.1 Oligarchic growth 131
8.3 Possibilities for boosting accretion speed and efficiency 136
  8.3.1 The role of protoplanet atmospheres 137
  8.3.2 Accretion in the shear-dominated regime 138
  8.3.3 Local enhancement of solids 140
8.4 Ice giants: the problem of Uranus and Neptune 141
8.5 Migration and survival 143
8.6 Discussion and conclusions 144

9 Planetary transits: a first direct vision of extrasolar planets 147
  Alain Lecavelier des Etangs and Alfred Vidal-Madjar
  9.1 Introduction 147
  9.2 Probability and frequency of transits 149
  9.3 Basics of transits
    9.3.1 Photometric transits 151
    9.3.2 Spectroscopic transits 153
  9.4 Observed photometric transits 153
    9.4.1 β Pictoris 153
    9.4.2 HD 209458b 154
    9.4.3 OGLE planets 155
    9.4.4 TrES-1 155
    9.4.5 Missing photometric transits 156
    9.4.6 The planet radius problem 156
  9.5 Observed spectroscopic transits 157
    9.5.1 β Pictoris 157
    9.5.2 HD 209458b 158
    9.5.3 Evaporation of hot Jupiters 159
    9.5.4 The search for transits with space observatories 161
  9.6 Conclusion 161
  Acknowledgments 162

10 The core accretion–gas capture model for gas-giant planet formation
  Olenka Hubickyj 163
  10.1 Introduction 163
  10.2 The development of the CAGC model 165
  10.3 Observational requirements for planet-forming models 167
  10.4 The CAGC computer model 169
  10.5 Recent results 173
  10.6 Summary 177
  Acknowledgments 178
## Contents

11 Properties of exoplanets: a Doppler study of 1330 stars  
*Geoffrey Marcy, Debra A. Fischer, R. Paul Butler, and Steven S. Vogt*  
179  
11.1 Overview of exoplanet properties and theory 179  
11.2 The Lick, Keck, and AAT planet searches 180  
11.3 Observed properties of exoplanets 181  
11.3.1 The planet–metallicity relationship 183  
11.4 The lowest-mass planets and multi-planet systems 184  
11.5 The Space Interferometry Mission 185  
11.5.1 Finding Earth-mass planets with SIM 186  
11.5.2 Low-mass detection threshold of SIM 186  
11.6 The synergy of SIM and Terrestrial Planet Finder (TPF)/Darwin 190  
Acknowledgments 191  

12 Giant-planet formation: theories meet observations  
*Alan Boss*  
192  
12.1 Introduction 192  
12.2 Gas-giant planet census 193  
12.3 Metallicity correlation 194  
12.4 Low-metallicity stars 196  
12.5 Gas-giant planets orbiting M dwarfs 197  
12.6 Core masses of Jupiter and Saturn 198  
12.7 Super-Earths and failed cores 199  
12.8 Gas-giant planet formation epochs 200  
12.9 Planetary-system architectures 201  
12.10 Conclusions 202  

13 From hot Jupiters to hot Neptunes . . . and below  
*Christophe Lovis, Michel Mayor, and Stéphane Udry*  
203  
13.1 Recent improvements in radial velocity precision 203  
13.2 Detecting planets down to a few Earth masses 205  
13.3 New discoveries and implications for planet-formation theories 208  
13.4 Update on some statistical properties of exoplanets 210  
13.4.1 Giant-planet occurrence 210  
13.4.2 Mass and period distributions 211  
13.4.3 Eccentricity distribution 213  
13.4.4 Metallicity of planet-host stars 214  

14 Disk–planet interaction and migration  
*Frederic Masset and Wilhelm Kley*  
216  
14.1 Introduction 216  
14.2 Type I migration 216  
14.2.1 Evaluation of the tidal torque 217
Contents

14.2.2 Corotation torque 222
14.2.3 Type I migration-drift rate estimates 223

14.3 Type II migration 224
14.3.1 Numerical modeling 224
14.3.2 Viscous laminar disks 225
14.3.3 The migration rate 227
14.3.4 Inviscid disks 228

14.4 Type III migration 230
14.5 Other modes of migration 234
14.6 Eccentricity driving 234

15 The brown dwarf–planet relation
Matthew R. Bate 236
15.1 Introduction 236
15.2 Masses 236
15.3 Evolution 239
15.4 The multiplicity of brown dwarfs 239
15.4.1 Binary brown dwarfs 240
15.4.2 Brown dwarfs as companions to stars 241
15.5 Formation mechanisms 241
15.5.1 Brown dwarfs from the collapse of low-mass molecular cores 242
15.5.2 Brown dwarfs from the competition between accretion and ejection 243
15.5.3 Brown dwarfs from evaporated cores 246
15.6 Planet or brown dwarf? 247
15.7 Conclusions 249
Acknowledgments 249

16 Exoplanet detection techniques – from astronomy to astrobiology
Wolfgang Brandner 250
16.1 Introduction: planet detection and studies in the historical context 250
16.2 Observing methods and ground/space projects 251
16.2.1 Indirect detection methods 252
16.2.2 Direct detection methods 253
16.3 Outlook: planet mapping and bio-signatures 254

17 Overview and prospective in theory and observation of planet formation
Douglas N. C. Lin 256
References 263
Index 300
Preface

With the words “Twas the night before Christmas…” does a good old story start. In December 2004, just a couple of days before Christmas, not three wise men but more than 60 wise men and women came to a castle in the Bavarian mountains. They traveled through a strong snow storm, but no-one turned back; all of them arrived. They had a noble goal in mind: to discuss the current understanding of the formation of planets. The meeting took place December 19–22, 2004 at the Ringberg castle of the Max-Planck-Society. Anyone who has had the chance to attend a meeting there knows what a friendly and stimulating atmosphere for a workshop it provides.

About a year beforehand we had called them, and now they came. The idea was to have a wonderful conference at the romantic Ringberg castle and to bring together theorists and observers, as well as meteoriticists and experimental astrophysicists. Only then, we thought, could we obtain a global picture of the ideas we have about how our planetary system came into life. We wanted to collect not only the accepted ideas, but also the speculative and competing ideas.

We were quickly convinced that this conference, unique in its composition, should generate a permanent record in the form of a proceedings book. But this book should not be just one more useless compendium of unrefereed papers, but should provide a concise and accurate picture of current planet formation theory, experiment, and observation. Based on a suggestion by Alan Boss, Cambridge University Press became interested in publishing the proceedings as part of its new astrobiology series. So we convinced some of the major league players in the planet-formation and extrasolar-planet business not only to come and give presentations but also to write overview chapters on their special field of expertise. These chapters were then publicly discussed at Ringberg and also refereed by some independent experts in the field.
Preface


PLANET FORMATION addresses fundamental questions concerning the formation of planetary systems in general and of our Solar System in particular. Drawing from recent advances in observational, experimental, and theoretical research, it summarizes our current understanding of these processes and addresses major open questions and research issues. We want this book to be, for students and other newcomers to the field, a detailed summary which, if studied along with the references contained herein, will provide sufficient information to start their work in the field of solar and extrasolar planets. At the same time we want to explore the current understanding of the state of the art of this subject ten years after the detection of the first extrasolar planets around Sun-like stars. The chapters of this book have been written by the leading scientists in the field, who have made significant contributions to the subject of planets and their formation. We aim for a comprehensive and meaningful overview including observations of exoplanets and circumstellar disks, the latest findings about our own Solar System, experiments on grain growth, and finally on the competing theories on planet formation.

If we continue to attract the brightest physicists to this field of astrophysics we hope that one day we will reach our two-fold goal: first, to understand the origin of our Solar System and of our blue Mother Earth, the only place in the universe where we are sure about the existence of life, and second, to learn how exquisite or general the conditions for life are in the rest of the vast universe, based on our predictions on how many Earth-like, potentially life-harboring planets are out there.
Acknowledgments

This book would have been impossible without the work of our contributors and referees. Thank you all! We are also indebted for the support here at the MPIA, foremost Anders Johansen for making “cvs” work. And most of all we want to thank Jacqueline Garget, our editor at Cambridge University Press, for her enthusiasm as well as patience during the production of the book.