UNIVERSE OR MULTIVERSE?

Recent developments in cosmology and particle physics, such as the string landscape picture, have led to the remarkable realization that our universe – rather than being unique – could be just one of many universes. The multiverse proposal helps to explain the origin of our universe and some of its observational features. Since the physical constants can be different in other universes, the fine-tunings that appear necessary for the emergence of life may also be explained. Nevertheless, many physicists remain uncomfortable with the multiverse proposal, since it is highly speculative and perhaps untestable.

In this volume, a number of active and eminent researchers in the field – mainly cosmologists and particle physicists but also some philosophers – address these issues and describe recent developments. The articles represent the full spectrum of views, from enthusiastic support of the multiverse to outright scepticism, providing for the first time a valuable overview of the subject. Contributions are written at varying academic levels, providing an engaging read for everyone. To preserve accessibility, mathematical equations are used in only a few chapters.

BERNARD CARR is Professor of Mathematics and Astronomy at Queen Mary, University of London (QMUL). His research interests include general relativity, the early universe, primordial black holes, dark matter and the anthropic principle. He regularly appears on television, for example on *The Sky at Night* and *Horizon*, and has published several dozen popular science articles. He is the author of nearly 200 technical papers and has worked in the USA, UK, Japan and Canada. He is a member of several learned societies, most notably the Royal Astronomical Society and the Institute of Physics. In 1984 he was awarded the Adams Prize by the University of Cambridge, one of the UK's most prestigious mathematical awards.

UNIVERSE OR MULTIVERSE?

Edited by

BERNARD CARR
Queen Mary, University of London

CAMBRIDGE
UNIVERSITY PRESS

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

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/9780521848411

First published 2007

Printed in the United Kingdom at the University Press, Cambridge

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

ISBN 978-0-521-84841-1 hardback

Contents

List of Contributors

Anthony Aguirre
Department of Physics, University of California, Santa Cruz, California 95064, USA

John D. Barrow
DAMTP, Centre for Mathematical Sciences, Cambridge University, Wilberforce Road, Cambridge CB3 0WA, UK

Nick Bostrom
Philosophy Faculty, Oxford University, 10 Merton Street, Oxford OX1 4JJ, UK

James D. Bjorken
Stanford Linear Accelerator Center, 2575 Sand Hill Road, Menlo Park, CA 94025, USA

Bernard Carr
Astronomy Unit, Queen Mary, University of London, Mile End Road, London E1 4NS, UK

Brandon Carter
Département d'Astrophysique Relativiste et Cosmologie, Observatoire de Paris, 5 Place J. Janssen, F-92195 Meudon Cedex, France

Robin Collins
Department of Philosophy, Messiah College, P.O. Box 245, Grantham, PA 17027, USA

Paul Davies
Beyond: Center for Fundamental Concepts in Science, Arizona State University, Temple, AZ 85281, USA

Savas Dimopoulos
Varian Physics Building, Stanford University, Stanford, CA 94305-4060, USA

John F. Donoghue
Department of Physics, University of Massachusetts, Amherst, MA 01003, USA

George Ellis
Department of Mathematics and Applied Mathematics, University of Cape Town, 7700 Rondebosch, South Africa

James B. Hartle
Physics Department, University of California, Santa Barbara, CA 93106, USA

Stephen Hawking
DAMTP, Centre for Mathematical Sciences, Cambridge University, Wilberforce Road, Cambridge CB3 0WA, UK

Craig J. Hogan
Astronomy and Physics Departments, University of Washington, Seattle, WA 98195-1580, USA

Renata Kallosh
Varian Physics Building, Stanford University, Stanford, CA 94305-4060, USA

Andrei Linde
Varian Physics Building, Stanford University, Stanford, CA 94305-4060, USA

Viatcheslav Mukhanov
Sektion Physik, Ludwig-Maximilians-Universtät, Theresienstr. 37, D-80333 Munich, Germany

Don N. Page
Department of Physics, University of Alberta, Edmonton, Alberta T6G 2J1, Canada

Martin J. Rees
Institute of Astronomy, Madingley Road, Cambridge CB3 0HA, UK

Lee Smolin
Perimeter Institute for Theoretical Physics, 35 King Street North, Waterloo, Ontario N2J 2W9, Canada

William R. Stoeger
Vatican Observatory Research Group, Steward Observatory, University of Arizona, Tucson, AZ 85719, USA

Leonard Susskind
Varian Physics Building, Stanford University, Stanford, CA 94305-4060, USA

Max Tegmark
Department of Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

Scott Thomas
Department of Physics and Astronomy, University of Rutgers, Piscataway, NJ 08854-8019, USA

Alexander Vilenkin
Department of Physics and Astronomy, Tufts University, Medford, MA 02155, USA

Steven Weinberg
Physics Department, University of Texas at Austin, Austin, TX 78712, USA

Frank Wilczek
Center for Theoretical Physics, MIT 6-305, 77 Massachusetts Avenue, Cambridge, MA 02139, USA

Preface

This book grew out of a conference entitled 'Universe or Multiverse?' which was held at Stanford University in March 2003 and initiated by Charles Harper of the John Templeton Foundation, which sponsored the event. Paul Davies and Andrei Linde were in charge of the scientific programme, while Mary Ann Meyers of the Templeton Foundation played the major administrative role. The meeting came at a critical point in the development of the subject and included contributions from some of the key players in the field, so I was very pleased to be invited to edit the resulting proceedings. All of the talks given at the Stanford meeting are represented in this volume and they comprise about half of the contents. These are the chapters by James Bjorken, Nick Bostrum, Robin Collins, Paul Davies, Savas Dimopoulos and Scott Thomas, Renata Kallosh, Andrei Linde, Viatschelav Mukhanov, Martin Rees, Leonard Susskind, Max Tegmark, Alex Vilenkin, and my own second contribution.

Several years earlier, in August 2001, a meeting on a related theme – entitled 'Anthropic Arguments in Fundamental Physics and Cosmology' – had been held in Cambridge (UK) at the home of Martin Rees. This was also associated with the Templeton Foundation, since it was partly funded out of a grant awarded to myself, Robert Crittenden, Martin Rees and Neil Turok for a project entitled 'Fundamental Physics and the Problem of Our Existence'. This was one of a number of awards made by the Templeton Foundation in 2000 as part of their 'Cosmology & Fine-Tuning' research programme. In our case, we decided to use the funds to host a series of workshops, and the 2001 meeting was the first of these.

The theme of the Cambridge meeting was somewhat broader than that of the Stanford one – it focused on the anthropic principle rather than the multiverse proposal (which might be regarded as a particular interpretation of the anthropic principle). Nevertheless, about half the talks were on the

multiverse theme, so I was keen to have these represented in the current volume. Although I had published a review of the Cambridge meeting in *Physics World* in October 2001, there had been no formal publication of the talks. In 2003 I therefore invited some of the Cambridge participants to write up their talks, albeit in updated form. I was delighted when almost everybody accepted this invitation, and their contributions represent most of the rest of the volume. These are the chapters by John Barrow, Brandon Carter, John Donoghue, George Ellis, James Hartle, Craig Hogan, Don Page, Lee Smolin, William Stoeger and Frank Wilczek.

We organized two further meetings with the aforementioned Templeton support. The second one – entitled 'Fine-Tuning in Living Systems' – was held at St George's House, Windsor Castle, in August 2002. The emphasis of this was more on biology than physics, and we were much helped by having John Barrow on the Programme Committee. Although this meeting was of great interest in its own right – representing the rapidly burgeoning area of astrobiology – there was little overlap with the multiverse theme, so it is not represented in this volume. Also, the proceedings of the Windsor meeting have already been published as a special issue of the *International Journal of Astrobiology*, which appeared in April 2003.

The third meeting was held at Cambridge in September 2005. It was again hosted by Martin Rees, but this time at Trinity College, Martin having recently been appointed Master of Trinity. The title of the meeting was 'Expectations of a Final Theory', and on this occasion David Tong joined the Programme Committee. Most of the focus was on the exciting developments in particle physics – in particular M-theory and the string landscape scenario, which perhaps provide a plausible theoretical basis for the multiverse paradigm. Many of the talks were highly specialized and – since this volume was already about to go to press – it was anyway too late to include them. Nevertheless, the introductory talk by Steven Weinberg and the summary talk by Franck Wilczek were very general and nicely complemented the articles already written. I was therefore delighted when they both agreed – at very short notice – to produce write-ups for this volume. The article by Stephen Hawking also derives from his presentation at the Trinity meeting, although he had previously spoken at the 2001 meeting as well. It is therefore gratifying that both Cambridge meetings – and thus all three Templeton-supported meetings – are represented in this volume.

Although I have described the history behind this volume, I should emphasize that the articles are organized by topic rather than chronology. After the overview articles in Part I, I have divided them into three categories. Part II focuses on the cosmological and astrophysical aspects of the

multiverse proposal; Part III is more relevant to particle physics and quantum cosmology; and Part IV addresses more general philosophical aspects. Of course, such a clean division is not strictly possible, since some of the articles cover more than one of these areas. Indeed, it is precisely the amalgamation of the cosmological and particle physical approaches which has most powered the growing interest in the topic. Nevertheless, by and large it has been possible to divide articles according to their degree of emphasis.

Although this book evolved out of a collection of conference papers, the articles are intended to be at semi-popular level (for example at the level of *Science* or *Scientific American*) and most of the contributions have been written by the authors with that in mind. However, there is still some variation in the length and level of the articles, and some more closely resemble in technicality the original conference presentations. Where papers are more technical, I have elaborated at greater length in my introductory remarks in order to make them more accessible. In my view, the inclusion of some technical articles is desirable, because it emphasizes that the subject is a proper branch of science and not just philosophy. Also it will hopefully broaden the book's appeal to include both experts and non-experts.

As mentioned in my Introduction, the reaction of scientists to the multiverse proposal varies considerably, and some dispute that it constitutes proper science at all. It should therefore be stressed that this is not a proselitizing work, and this is signified by the question mark in the title. I did briefly consider the shorter title 'Multiverse?' or even 'Multiverse' (without the question mark), but I eventually discarded these as being too unequivocal. In fact, the authors in this volume display a broad range of attitudes to the multiverse proposal – from strong support through open-minded agnosticism to strong opposition. The proponents probably predominate numerically and they are certainly more represented in Parts II and III. However, the balance is restored in Part IV, where many of the contributors are sceptical. Therefore readers who persevere to the end of this book are unlikely to be sufficiently enlightened to answer the question raised by its title definitively. Nevertheless, it is hoped that they will be stimulated by the diversity of views expressed. Finally, it should be stressed that perhaps the most remarkable aspect of this book is that it testifies to the large number of eminent physicists who now find the subject interesting enough to be worth writing about. It is unlikely that such a volume could have been produced even a decade ago!

Bernard Carr

Acknowledgements

This volume only exists because of indispensable contributions from various people involved in the three conferences on which it is based. First and foremost, I must acknowledge the support of the John Templeton Foundation, which hosted the Stanford meeting in 2003 and helped to fund the two Cambridge meetings in 2001 and 2005. I am especially indebted to Charles Harper, the project's initiator, and his colleague Mary Ann Meyers, director of the 'Humble Approach Initiative' programme, who played the major administrative role in the Stanford meeting and subsequently helped to oversee the progress of this volume. Special credit is also due to Paul Davies and Andrei Linde, who were in charge of the scientific programme for the Stanford meeting and conceived the title, which this book has inherited. The Templeton Foundation indirectly supported the Cambridge meetings, since these were partly funded from a Templeton grant awarded to myself, Robert Crittenden, Martin Rees and Neil Turok. I would like to thank my fellow grant-holders for a most stimulating collaboration. They undertook most of the organizational work for the Cambridge meetings, along with David Tong, who joined the Programme Committee for the 2005 meeting. I am especially indebted to Martin Rees, not only for hosting the two Cambridge meetings, but also for triggering my own interest in the subject nearly thirty years ago and for encouraging me to complete this volume. I am very grateful to various people at Cambridge University Press for helping to bring this volume to fruition: the editor Simon Capelin, who first commissioned the book; the editor John Fowler, who made some of the later editorial decisions and showed great diplomacy in dealing with my various requests; the production editors Jacqui Burton and Bethan Jones; and especially the copy-editor Irene Pizzie, who went though the text so meticulously, suggested so many improvements and dealt with my continual stream of changes so patiently. Most indispensable of all were the contributors themselves, and I would like to thank them for agreeing to write up their talks and for dealing with all my editorial enquiries so patiently. Finally, I would like to thank my dear wife, Mari, for her love and support and for patiently putting up with my spending long hours in the office in order to finish this volume.

Editorial note

Although the term 'universe' is usually taken to mean the totality of creation, the theme of this book is the possibility that there could be other universes (either connected or disconnected from ours) in which the constants of physics (and perhaps even the laws of nature) are different. The ensemble of universes is then sometimes referred to as the 'multiverse', although not everybody likes that term and several alternatives are used in this volume (for example, megaverse, holocosm, and parallel worlds).

This lack of consensus on what term to use is hardly surprising, since the concept of a multiverse has arisen in many different contexts. Therefore, in my role as editor, I have not attempted to impose any particular terminology and have left authors to use whatever terms they wish. However, in so much as most authors use the word 'universe', albeit in different contexts, I have tried to impose uniformity in whether the first letter is upper or lower case. Although this might be regarded as a minor and rather pedantic issue, I feel that a book entitled *Universe or Multiverse?* should at least address the problem, and this distinction in notation can avoid ambiguities.

I have adopted the convention of using 'Universe' (with a big U) when the author is (at least implicitly) assuming that ours is the only one. When the author is (again implicity) referring to a general member of an ensemble (or just an abstract mathematical model), the term 'universe' (with a small u) is generally used. The particular one we inhabit is then described as 'our universe', although the phrase 'the Universe' (with a big U) is also sometimes used. This mirrors the way in which astronomers refer to 'our galaxy' as 'the Galaxy', and allows a useful distinction to be drawn (for example) between 'the visible Universe' (i.e. the visible part of our universe) and 'the visible universe' (i.e. the universe of which a part is visible to us). The word 'multiverse' is always spelt with a small m, since the idea arises in different ways, so there could be more than one of them.

Some authors prefer to reserve the appellation 'Universe' for the ensemble itself, perhaps preserving the term 'multiverse' for some higher level ensemble. In this case a capital U is used. In the inflationary scenario, for example, the term 'Universe' would then be used to describe the whole collections of bubbles rather than any particular one. This issue also arises in the context of quantum cosmology, which implicitly assumes the 'many worlds' interpretation of quantum mechanics. The literature in this field commonly refers to the 'wave-function of the Universe', although one might argue that wave-function is really being taken over a multiverse. The title of this book can therefore be understood to refer not only to the ontological issue of whether other universes exist, but also to the etymological issue of what to call the ensemble!

Cover picture

The picture on the cover is a tri-dimensional representation of the quadri-dimensional Calabi-Yau manifold. This describes the geometry of the extra 'internal' dimensions of M-theory and relates to one particular (string-inspired) multiverse scenario. I am grateful to Dr Jean-Francois Colonna of CMAP/Ecole Polytechnique, FT R&D (whose website can be found at http://www.lactamme.polytechnique.fr) for allowing me to use this picture. The orange background represents the 'fire' in the equations and is a modification of a design originally conceived by Cindy King of King Design Group. A similar image was first used in the poster for the second meeting on which this book is based (at Stanford in 2003).