Gravity and Strings

One appealing feature of string theory is that it provides a theory of quantum gravity. *Gravity and Strings* is a self-contained, pedagogical exposition of this theory, its foundations, and its basic results.

In Part I, the foundations are traced back to the very early special-relativistic field theories of gravity, showing how such theories, which are associated with the concept of the graviton, lead to general relativity. Gauge theories of gravity are then discussed and used to introduce supergravity theories.

Part II covers some of the most interesting solutions of general relativity and its generalizations. These include Schwarzschild and Reissner–Nordström black holes, the Taub–NUT solution, gravitational instantons, and gravitational waves. Kaluza–Klein theories and the uses of residual supersymmetries are discussed in detail.

Part III presents string theory from the effective-action point of view, using the results found earlier in the book as background. The supergravity theories associated with superstrings and M theory are thoroughly studied, and used to describe dualities and classical solutions related to non-pertubative states of these theories. A brief account of extreme black-hole entropy calculations is also given.

This unique book will be useful as a reference for graduate students and researchers, as well as a complementary textbook for courses on gravity, supergravity, and string theory.

TOMÁS ORTÍN completed his graduate studies and obtained his Ph.D. at the Universidad Autónoma de Madrid. He then worked as a postdoctoral student in the Physics Department of Stanford University supported by a Spanish Government grant. Between 1993 and 1995 he was EU Marie Curie postdoctoral fellow in the String Theory Group of the Physics Department of Queen Mary College, University of London, and from 1995 to 1997, he was a Fellow in the Theory Division of CERN. He is currently a Staff Scientist at the Spanish Research Council and a member of the Institute for Theoretical Physics of the Universidad Autónoma de Madrid. Dr Ortín has taught several graduate courses on advanced general relativity, supergravity, and strings. His research interests lie in string theory, gravity, quantum gravity, and black-hole physics.

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To Marimar, Diego, and Tomás,
the sweet strings that tie me to
the real world

Contents

Preface

String theory has lived for the past few years during a golden era in which a tremendous upsurge of new ideas, techniques, and results has proliferated. In what form they will contribute to our collective enterprise (theoretical physics) only time can tell, but it is clear that many of them have started to have an impact on closely related areas of physics and mathematics and, even if string theory does not reach its ultimate goal of becoming a theory of everything, it will have played a crucial, inspiring role.

There are many interesting things that have been learned and achieved in this field that we feel can (and perhaps should) be taught to graduate students. However, we have found that this is impossible without the introduction of many ideas, techniques, and results that are not normally taught together in standard courses on general relativity, field theory or string theory, but which have become everyday tools for researchers in this field: black holes, strings, membranes, solitons, instantons, unbroken supersymmetry, Hawking radiation.... They can, of course, be found in various textbooks and research papers, presented from various viewpoints, but not in a single reference with a consistent organization of the ideas (not to mention a consistent notation).

These are the main reasons for the existence of this book, which tries to fill this gap by covering a wide range of topics related, in one way or another, to what we may call *semiclassical string gravity*. The selection of material is according to the author's taste and personal preferences with the aim of self-consistency and the ultimate goal of creating a basic, pedagogical, reference work in which all the results are written in a consistent set of notations and conventions. Some of the material is new and cannot be found elsewhere.

Precisely because of the blend of topics we have touched upon, although a great deal of background material is (briefly) reviewed here, this cannot be considered a textbook on general relativity, supergravity or string theory. Nevertheless, some chapters can be used in graduate courses on these matters, either providing material for a few lectures on a selected topic or combined (as the author has done with the first part, which is self-contained) into an advanced (and a bit eclectic) course on gravity.

It has not been too difficult to order logically the broad range of topics that had to be discussed, though. We can view string theory as the summit of a pyramid whose building blocks are the theories, results, and data that become more and more fundamental and basic the more we approach the base of the pyramid. At the very bottom (Part I) one can find tools

such as differential geometry and the use of symmetry in physics and fundamental theories of gravity such as general relativity and extensions to accommodate fermions such as the CSK theory and supergravity. The rest of the book is supported by it. In particular, we can see string theory as the culmination of long-term efforts to construct a theory of quantum gravity for a spin-2 particle (the graviton) and our approach to general relativity as the only self-consistent classical field theory of the graviton is intended to set the ground for this view.

Part II investigates consequences, results, and extensions of general relativity through some of its simplest and most remarkable solutions, which can be regarded as point-particle-like: the Schwarzschild and Reissner–Nordström solutions, gravitational waves, and the Taub-NUT solution. In the course of this study we introduce the reader to black holes, "no-hair theorems," black-hole thermodynamics, Hawking radiation, gravitational instantons, charge quantization, electric–magnetic duality, the Witten effect etc. We will also explain the essentials of dimensional reduction and will obtain black-hole solutions of the dimensionally reduced theory. To finish Part II we introduce the reader to the idea and implications of residual supersymmetry. We will review all our results on black-hole thermodynamics and other black-hole properties in the light of unbroken supersymmetry.

Part III introduces strings and the string effective action as a particular extension of general relativity and supergravity. String dualities and extended objects will be studied from the string-effective-action (spacetime) point of view, making use of the results of Parts I and II and paying special attention to the relation between worldvolume and spacetime phenomena. This part, and the book, closes with an introduction to the calculation of black-hole entropies using string theory.

During these years, I have received the support of many people to whom this book, and I personally, owe much: Enrique Álvarez, Luis Álvarez-Gaumé, and my long-time collaborators Eric Bergshoeff and Renata Kallosh encouraged me and gave me the opportunity to learn from them. My students Natxo Alonso-Alberca, Ernesto Lozano-Tellechea, and Patrick Meessen used and checked many versions of the manuscript they used to call the *PRC*. Their help and friendship in these years has been invaluable. Roberto Emparan, José Miguel Figueroa-O'Farrill, Yolanda Lozano, Javier Más, Alfonso Vázquez-Ramallo, and Miguel Ángel Vázquez-Mozo read several versions of the manuscript and gave me many valuable comments and advice, which contributed to improving it. I am indebted to Arthur Greenspoon for making an extremely thorough final revision of the manuscript.

Nothing would have been possible without Marimar's continuous and enduring support.

If, in spite of all this help, the book has any shortcomings, the responsibility is entirely mine. Comments and notifications of misprints can be sent to the e-mail address `tomas.ortin@uam.es`. The *errata* will be posted in `http://gesalerico.ft.uam.es/prc/misprints.html`.

This book started as a written version of a review talk on string black holes prepared for the first String Theory Meeting of the Benasque Center for Theoretical Physics, back in 1996, parts of it made a first public appearance in a condensed form as lectures for the charming Escuela de Relatividad, Campos y Cosmología "La Hechicera" organized by the Universidad de Los Andes (Mérida, Venezuela), and it was finished during a long-term visit to the CERN Theory Division. I would like to thank the organizers and members of these institutions for their invitations, hospitality, and economic support.