BLACK HOLES IN HIGHER DIMENSIONS

Black holes are one of the most remarkable predictions of Einstein's general relativity. Now widely accepted by the scientific community, most work has focused on black holes in our familiar four spacetime dimensions. In recent years, however, ideas in brane-world cosmology, string theory, and gauge/gravity duality have all motivated a study of black holes in more than four dimensions, with surprising results. In higher dimensions, black holes exist with exotic shapes and unusual dynamics.

Edited by leading expert Gary Horowitz, this exciting book is the first devoted to this new field. The major discoveries are explained by the people who made them: for example, Rob Myers describes the Myers–Perry solutions that represent rotating black holes in higher dimensions; Ruth Gregory describes the Gregory–Laflamme instability of black strings; and Juan Maldacena introduces gauge/gravity duality, the remarkable correspondence that relates a gravitational theory to nongravitational physics. There are two additional chapters on this duality, explaining how black holes can be used to describe relativistic fluids and aspects of condensed matter physics.

Accessible to anyone who has taken a standard graduate course in general relativity, this book provides an important resource for graduate students and for researchers in general relativity, string theory, and high energy physics.

GARY T. HOROWITZ is a professor of physics at the University of California, Santa Barbara. He has made numerous contributions to classical and quantum gravity. In particular, he (co-)discovered a class of higher-dimensional black holes called "black branes". Professor Horowitz is a member of the National Academy of Science, a Fellow of the American Physical Society, and a member of the International Committee for the General Relativity and Gravitation Society. He has won the Xanthopoulos Prize in general relativity and has written over 150 research articles.

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Preface

Black holes are one of the most striking predictions of general relativity. Their main classical properties were understood by the 1970s. In particular, it had been shown that they are very simple objects: stationary vacuum black holes are uniquely characterized by their mass and angular momentum. Astrophysical evidence for black holes has improved dramatically over the past decade and it is now widely accepted that black holes are ubiquitous in our universe.

Naturally enough, the work through the 1970s was focused on black holes in our familiar four spacetime dimensions ($D = 4$). Recently, there has been an explosion of interest in higher-dimensional black holes. There are at least four reasons for this.

(1) As mentioned above, black holes in $D = 4$ are special: they must be spherical, specified by a few parameters, always stable, etc. It is natural to ask whether these properties are characteristic of black holes in general or just a result of four spacetime dimensions.

(2) Recent brane-world ideas suggest that our familiar three spatial dimensions might just be a surface in a higher-dimensional space. In these theories, nongravitational forces are confined to the brane but gravity is higher dimensional. So black holes extend into the extra dimensions.

(3) String theory, one of the most promising approaches to quantum gravity, predicts that spacetime has more than four dimensions. This incorporates older ideas of unification based on the idea that extra dimensions are curled up into a small ball. So, in string theory we must consider higher-dimensional black holes.

(4) Gauge/gravity duality, which has emerged from string theory, relates certain strongly coupled nongravitational theories to higher-dimensional theories with gravity. Under this duality, thermal equilibrium in some (3+1)-dimensional nongravitational systems is described by a higher-dimensional black hole.

Over the past two decades we have learned that higher-dimensional black holes are much less constrained than their cousins in $D = 4$. They do not have to be spherical, and they are not uniquely determined by their mass and angular momentum. In addition, they have more interesting dynamics, since some stationary black holes are unstable. This instability causes the horizon to pinch off in finite time, producing a singularity that is visible from infinity, i.e., a naked singularity. So while there is strong evidence that naked singularities cannot form generically in four-dimensional general relativity, they do form generically in higher dimensions.

Given all these exciting results, the time is right for a book devoted to higher-dimensional black holes and some of their applications. I have asked people who have made significant contributions to this subject to explain them for this edited volume. The book is not an exact-solutions manual, with all known $D > 4$ black hole solutions included. Since the field is still progressing, that would quickly become obsolete. Instead, while it includes the most important explicitly known solutions, it focuses on general properties of higher-dimensional black holes and their recent applications to other areas of physics.

The book is divided into five parts. The first gives a brief introduction, reviewing the familiar four-dimensional black holes. The next part is devoted to five-dimensional Kaluza–Klein theory. This is the oldest approach to higher dimensions, in which one adds a single compact extra dimension to general relativity. This is the simplest setting in which to introduce the Gregory–Laflamme instability (described in a chapter by Ruth Gregory) and the resulting pinch-off of the horizon (explained by Luis Lehner and Frans Pretorius). There is also a chapter (by Toby Wiseman and Gary Horowitz) on general Kaluza–Klein black holes, including solutions that are homogeneous in the extra dimension and those that are not.

In Part III some asymptotically flat higher dimensional black holes are described. The higher-dimensional analogues of the Kerr solution are Myers–Perry black holes (described in a chapter by Rob Myers). The first nonspherical black hole was the black ring discovered by (and explained by) Roberto Emparan and Harvey Reall. After these analytic solutions, the next part focuses on more general higher-dimensional black holes. There is a chapter by Greg Galloway on the possible topologies of higher-dimensional horizons, and a chapter by Roberto Emparan on blackfolds – a way of approximately constructing higher-dimensional black holes that realize some of these nontrivial topologies. Harvey Reall describes algebraically special solutions in higher dimensions and Toby Wiseman explains how to numerically construct general static and stationary black holes.

Essentially everything up to this point is based on the (higher-dimensional) Einstein equation with zero matter. The final section (which is more than a third of the book) adds some interesting matter fields and describes the recent applications of black holes to other areas of physics. It starts with a chapter by Don Marolf introducing the black holes and branes of ten- and eleven-dimensional supergravity. Juan Maldacena then explains the basic ideas behind the remarkable gauge/gravity duality, which allows us to relate general relativity to nongravitational physics. Taking the long-wavelength limit of this duality yields a fluid/gravity correspondence (described in a chapter by Veronika Hubeny, Shiraz Minwalla, and Mukund Rangamani). Finally, Sean Hartnoll explains some aspects of the most recent application of gauge/gravity duality, namely to condensed matter physics.

A common theme is the connection between black hole horizons and fluid dynamics. This had already been noticed in the 1980s, with the development of the membrane paradigm, but it has become much more refined in recent years. Similarities to fluids are found in the way the horizon pinches off (Chapter 3), in the effective dynamics of black branes (Chapter 8) and, of course, the fluid/gravity correspondence (Chapter 13).

The book is pedagogical in style, and in most chapters it is assumed only that the reader has taken a standard course on general relativity. (Some chapters in the last part perhaps require a somewhat broader background.) The book should be a useful reference for students and researchers in string theory, high energy theory, and gravitational physics. Owing to the developments described in the final chapter, it may also be of interest to some condensed matter physicists.

I would like to thank the chapter authors for agreeing to contribute to this project and for writing excellent introductions or reviews of their respective topics. They made my job as editor as painless as possible. I also thank the National Science Foundation for providing funding for my research. Finally, I wish to thank my wife, Corinne, for her constant support.

Gary T. Horowitz