GRAVITY'S FATAL ATTRACTION

Black Holes in the Universe

Third Edition

Richly illustrated with images from observatories on the ground and in space, and computer simulations, this book shows how black holes were discovered, and discusses what we've learned about their nature and their role in cosmic evolution.

This thoroughly updated third edition covers new discoveries made in the past decade, including the discovery of gravitational waves from merging black holes and neutron stars, the first close-up images of the region near a black hole event horizon, and observations of debris from stars torn apart when they ventured too close to a supermassive black hole.

Avoiding math, the authors blend theoretical arguments with observational results to demonstrate how both have contributed to the subject. Clear, explanatory illustrations and photographs reveal the strange and amazing workings of our Universe. The engaging style makes this book suitable for introductory undergraduate courses, amateur astronomers, and all readers interested in astronomy and physics.

Mitchell Begelman is a Professor of Distinction in Astrophysical and Planetary Sciences and a fellow of JILA, at the University of Colorado Boulder. He has won several awards, including a Guggenheim Fellowship, Sloan Research Fellowship, the American Astronomical Society Warner Prize, and the American Institute of Physics Science Writing Award (with Martin Rees, for the first edition of *Gravity's Fatal Attraction*). He is also the author of *Turn Right at Orion: Travels through the Cosmos*.

Martin Rees is the UK's Astronomer Royal, a fellow (and former Master) of Trinity College, and was President of the Royal Society from 2005 to 2010. He is a foreign associate of the National Academy of Sciences, the Russian Academy of Sciences, the Pontifical Academy, the Japan Academy, and several other foreign academies. His awards include the Balzan Prize, the Bower Award, the Gruber Prize, the Crafoord Prize, and the Templeton Prize. In addition to his research publications, he has written extensively for a general readership. His ten other books include *Before the Beginning, Just Six Numbers, Our Cosmic Habitat*, and *On the Future: Prospects for Humanity*.

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Mitchell Begelman
University of Colorado Boulder

Martin Rees
University of Cambridge

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University Printing House, Cambridge CB2 8BS, United Kingdom

One Liberty Plaza, 20th Floor, New York, NY 10006, USA

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Preface to the Third Edition

As early as 1967 black holes were creeping into public consciousness. On the television program *Star Trek*, Captain Kirk and the crew of the starship *Enterprise* were caught in the gravitational field of an "uncharted black star" and were propelled backward in time. Astronomers then had no clue whether black holes were real or just theoreticians' constructs. Certainly no serious evidence of their reality existed, and few would have guessed that they would soon become the object of intense astronomical study. Until the 1970s, the black hole was still a novel concept, studied by specialists in Einstein's general theory of relativity. And that theory itself (though already several decades old) had only tentative empirical support. Gravity, one of the fundamental forces of nature, was still poorly understood.

Thanks to technological advances in observational astronomy – new detectors and mirror designs in optical telescopes, radio telescopes that offer far sharper images than even the best optical instruments, and observations made from space, revealing the sky at infrared, ultraviolet, X-ray, and gamma-ray wavelengths – we are now confident that there are millions of black holes in every galaxy. Each of these holes is the remnant of an ordinary star several times more massive than the Sun. More remarkably, giant black holes, weighing as much as millions (or even billions) of suns, lurk in the centers of most galaxies. The most energetic phenomena in the Universe – quasars, and jets a million light-years long erupting from the centers of galaxies – are powered by black holes. The same phenomena, in miniature, are energized by the smaller holes within our own Galaxy.

This book describes the extraordinary ways in which black holes make their presence known. We discuss the designs and accidents through which they were discovered, and how far we have come toward understanding their relationship to other structures in the cosmos. Every advance in technology has disclosed an assortment of dazzling, unexpected phenomena. Some of these phenomena, like gravitational lenses, are well understood and are being co-opted as tools in the search for black holes and other forms of "dark matter"; others, such as gamma-ray bursts, remain poorly understood. In between lies a range of phenomena for which understanding is substantial but incomplete: the processes and flow patterns around black holes; how the first ones formed; and the two-way interactions between supermassive holes and their host galaxies. And new questions for the future are constantly arising. What can we learn from gravitational waves now that these are detectable? How much could black holes contribute to the dark matter in the Universe? Could microscopic holes exist – the size of an atomic nucleus but the weight of a mountain? As the Universe evolves, what is the ultimate fate of matter swallowed by black holes?

As theorists in a profession heavily dominated (and rightly so) by observers, we demand empirical proof that black holes exist, and are eager for evidence on whether they have the properties predicted by Einstein's theory. Is there a "smoking gun" that removes all doubt of their existence, or of their ubiquity at the level we claim? When the first edition of the book appeared (in 1995) there were still some doubts. But the evidence has strengthened tremendously since then, and our understanding of the role of black holes in the Universe has deepened as well. In the second edition (2010) we substantially rewrote several chapters and included much new material on gamma-ray bursts and cosmic feedback.

We now present a fully updated third edition. We highlight the advances that have stemmed from new and more sensitive instruments – some even capable of "imaging" a black hole – and how surveys of the whole sky have provided far larger samples of the various classes of exotic objects that populate the Universe. Equally crucial have been the vast improvements in computer power. Astronomers cannot, of course, directly experiment on cosmic objects: they are passive observers of the cosmos. But they can conduct experiments in the virtual world of a computer. Such simulations have greatly deepened our understanding of how black holes form, and of the flow patterns of the magnetized gas that swirls around them, emitting intense radiation and generating jet-like outflow. Images, from observations and simulations alike, have been updated to reflect both the enhanced sensitivity and resolution of real images, and the increasing sophistication of theoretical models.

And we have added a chapter on the most spectacular new probe of black holes: gravitational waves. The LIGO and VIRGO detectors are an amazing technical triumph, opening up a new window on the cosmos. They have detected "ripples" in spacetime due to the mergers of black holes. We expect an accelerating rate of detections as the instrumentation improves, but even the initial discoveries revealed some surprises about the population of black holes in the cosmos – as well as offering seeming confirmation of Einstein's theory in contexts where spacetime is strongly distorted, and sloshing around in a dynamic state.

These cosmic "fireworks," spectacular as they are, may ultimately prove to be stepping stones to even more profound knowledge. Shrouded from view, deep inside black holes, lurk mysteries that will not be understood without a unification of Einstein's theory of gravity with the other great pillar of twentieth-century physics, the quantum theory. Such new insights, when they are achieved, may change our view of the nature of time, and of our entire Universe. The evidence that black holes indeed exist strengthens the motivation for this fundamental quest.

Research in astrophysics is, for us, an intensely interactive activity. Many observers have generously discussed their latest work with us; we have also benefited from other theorists who have special knowledge and expertise that we lack. We especially acknowledge all we have learned from Roger Blandford, a frequent collaborator throughout our careers. We are fortunate to have been inspired by long association with two great scientists, now sadly deceased: Stephen Hawking and Donald Lynden-Bell. And to have had among our immediate colleagues leading authorities such as Andrew Fabian, Richard McCray, Christopher Reynolds, and Philip Armitage. We are grateful to them, and to our many other collaborators. We are also grateful to many colleagues who took the time to prepare illustrations – often of results "hot off the press," or even prepublication.

We have been especially fortunate in our publisher and editors – Jonathan Cobb, Susan Moran, and Nancy Brooks of Freeman helped with the first edition. And we remain grateful to Colin Norman, Joseph Silk, and Virginia Trimble for offering helpful comments on that edition. We are grateful to our respective staffs – especially Judith Moss in Cambridge and Elaine Verdill and her colleagues in Boulder – for keeping the three-way exchange of text and pictures running smoothly during those (more or less) pre-Internet days. We thank Simon Mitton for his help and encouragement in getting the second edition commissioned at Cambridge University Press, and Vince Higgs for his expert guidance in seeing through both the second edition and this one. We are also grateful to the exceptional CUP staff for their editorial assistance.