

Theory and Experiment in Gravitational Physics

The 2015 centenary of the publication of Einstein's general theory of relativity and the first detection of gravitational waves have focused renewed attention on the question of whether Einstein was right.

This review of experimental gravity provides a detailed survey of the intensive testing of Einstein's theory of gravity, including tests in the emerging strong-field dynamical regime. It discusses the theoretical frameworks needed to analyze gravitational theories and interpret experiments. Completely revised and updated, this new edition features coverage of new alternative theories of gravity, a unified treatment of gravitational radiation, and the implications of the latest binary pulsar observations. It spans the earliest tests involving the solar system to the latest tests using gravitational waves detected from merging black holes and neutron stars. It is a comprehensive reference for researchers and graduate students working in general relativity, cosmology, particle physics, and astrophysics.

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For Leslie

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Preface

The year 2015 marked the 100th anniversary of the publication of Einstein’s general theory of relativity, and relativists worldwide celebrated this historic occasion. As if this were not enough, on September 14, 2015, scientists at the LIGO gravitational-wave observatories in the United States detected, for the first time, gravitational waves passing the Earth, emitted by a pair of merging black holes over a billion light years away. This event provided a kind of fairy-tale capstone to a remarkable century.

Indeed, some popular accounts of the history of general relativity read like a fairy tale, going something like this: in 1905, Einstein discovered special relativity. He then turned his attention to general relativity and after ten years of hard work, he got general relativity in November 1915. In 1919, Eddington verified the theory by measuring the bending of starlight during a solar eclipse. Einstein became famous. And everybody lived happily ever after.

The real history of general relativity is rather more complex. At the time of Eddington’s measurements of light bending, there was considerable skepticism about the results. There were major conceptual difficulties with the theory; it was very hard to understand what this new theory was and what it really predicted. And finally, there was an abiding sense that the theory mainly predicted some very tiny corrections to Newtonian gravity, and that it really wasn’t all that important for physics.

As a result, within about ten years of its development, general relativity entered a period of decline, dubbed the “low-water mark” by Jean Eisenstaedt (2006), so that by the end of the 1950s, general relativity was considered to be in the backwaters of physics and astronomy, not a fit subject for a serious scientist to pursue.

But during the 1960s there began a remarkable renaissance for the theory. This was driven in part by the discovery of quasars, pulsars, and the cosmic background radiation, systems where it became clear that general relativity would play a central role. It was also fueled by the beginnings of a worldwide effort to put the theory to the test using new precision tools such as atomic clocks and radio telescopes, together with the emerging space program. And gravitational theorists developed a variety of tools that allowed them to clarify what the theory and its competitors predicted, analyze the new experimental results, and devise new tests.

Today, general relativity is fully integrated into the mainstream of physics, and in fact is central to some of the key scientific questions of today, such as: How did the universe begin and what is its future? What governs physics at the shortest distances and the longest distances? Do black holes really exist and how do they affect their surroundings? How can we reconcile gravity and quantum mechanics?

Yet, is it the correct theory of gravity? Was Einstein really right?

By the time of the centenary of general relativity, Einstein's theory had been tested in many ways and to high precision, and had passed every test. So far, no experiment has been able to put an unambiguous dent in the armor of general relativity. And yet "experimental gravity" is as active and exciting a field as it was in 1981, when the first edition of this book came out. This is motivated in part by the ongoing mysteries and conundra associated with the acceleration of the universe, the apparent existence of dark matter, and the difficulty of marrying general relativity with quantum mechanics.

But it is also motivated by our newfound ability to explore regimes for testing Einstein's theory far beyond the relatively weak and benign realms of the laboratory and the solar system. This exploration began, of course, with the discovery of the binary pulsar in 1974, leading to the first tests involving neutron stars, but in recent years it has accelerated dramatically.

As we look toward the second century of general relativity, two important themes are going to be (i) testing general relativity in the strong-gravity regime near black holes and neutron stars, going beyond the weak-gravity conditions of the solar system and (ii) testing general relativity in the highly dynamical regime, where gravitational radiation is both a phenomenon to be scrutinized and a tool for studying dynamical, strong-gravity sources.

There is no better illustration of this new era for testing general relativity than the outpouring of papers following the first detections of gravitational waves by the LIGO-Virgo collaboration, showing how the data place new and compelling constraints on a wide range of alternative theories, in ways that would not have been possible using solar-system measurements. It is my hope that this book will serve not only as an update of the 1981 edition but also as a foundation for students and researchers who wish to join in this new effort to check whether Einstein was right.

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Over my fifty-year-long adventure in the world of testing general relativity, it has been my great fortune to have had three inspiring mentors: Kip Thorne, Subrahmanyan Chandrasekhar, and Bob Wagoner. Kip assigned me the PhD project of figuring out what had to be done to test general relativity better. He also taught by example the ways of research, teaching, scientific writing, and presenting science to broad audiences. From Chandra I learned a style of meticulous attention to detail in calculations that has been a hallmark of my own research. He also gave me a deep appreciation for science history. Bob's infectious enthusiasm for physics and astronomy taught me that, if you aren't having fun doing this work, you're in the wrong business. I have always had fun!

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