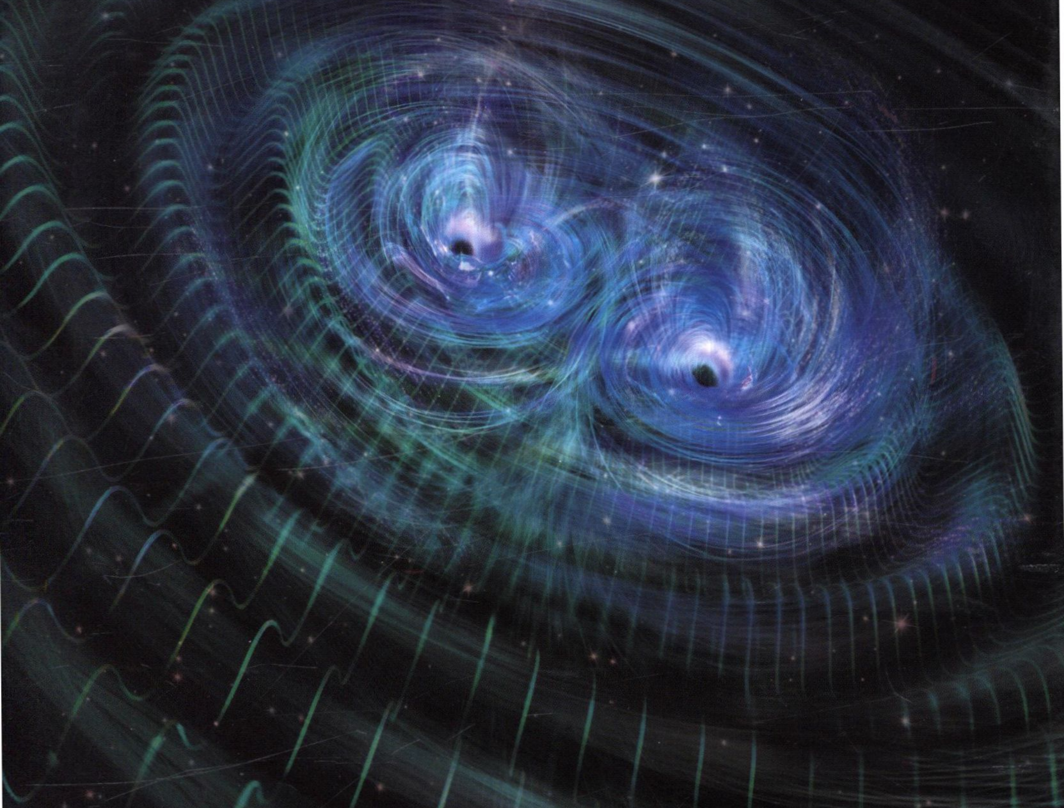
GOVERT SCHILLING

WITH A FOREWORD BY MARTIN REES



RIPPLES IN SPACETIME

EINSTEIN, GRAVITATIONAL WAVES, AND THE FUTURE OF ASTRONOMY

"In this elegant and captivating book Govert Schilling takes us by the hand through a century of scientific adventures to one of the biggest discoveries of history."

—Robbert Dijkgraaf, Director and Leon Levy Professor, Institute for Advanced Study

"I read with great pleasure this friendly book. The placement of the detection of gravitational waves in the greater history of astronomy and physics is nicely done, and readers not yet familiar with many of the concepts will come away from the book having really learned some of the physics as well as having a sense of what real science and real scientists are like. The scope and organization makes it entertaining and leaves room for surprises."

—David Shoemaker, Spokesperson, LIGO Scientific Collaboration and Senior Research Scientist, MIT Kavli Institute

ISBN: 978-0-674-97166-0
90000
9 780674 971660

SCHILLING

RIPPLES IN SPACETIME

Belknap
Harvard

RIPPLES IN SPACETIME

((( )))

Einstein, Gravitational Waves, and the Future of Astronomy

GOVERT SCHILLING

The Belknap Press of Harvard University Press
Cambridge, Massachusetts | London, England
2017

Printed in the United States of America
Second printing

Library of Congress Cataloging-in-Publication Data

Names: Schilling, Govert, author.
Title: Ripples in spacetime : Einstein, gravitational waves, and the future of astronomy / Govert Schilling.
Description: Cambridge, Massachusetts : The Belknap Press of Harvard University Press, 2017. | Includes bibliographic references and index.
Identifiers: LCCN 2017007571 | ISBN 9780674971660 (alk. paper)
Subjects: LCSH: Gravitational waves. | Relativistic astrophysics—Methodology. | Einstein, Albert, 1879–1955.
Classification: LCC QC179 .S287 2017 | DDC 539.7/54—dc23
LC record available at https://lccn.loc.gov/2017007571

RIPPLES IN SPACETIME

Foreword

MARTIN REES

Einstein has a unique place in the pantheon of science—and deservedly so. His insights into space and time have transformed our understanding of gravity and the cosmos. Everyone recognizes the benign and unkempt sage of poster and T-shirt. But his best work was done when he was young. He was still in his thirties when he was catapulted to worldwide fame. On May 29, 1919, there was a solar eclipse. A group led by the astronomer Arthur Eddington observed stars appearing close to the Sun during the eclipse. The measurements showed that these stars were displaced from their normal positions, the light from them being bent by the Sun's gravity. This confirmed one of Einstein's key predictions. When these results were reported at the Royal Society in London, the world press spread the news. "Lights All Askew in the Heavens; Einstein Theory Triumphs" was the rather over-the-top headline in the *New York Times*.

Einstein's theory of general relativity, put forward in 1915, is a triumph of pure thought and insight. Its implications for us on Earth are slight. It requires minor adjustments in the clocks used in modern navigation systems, but Newton remains good enough for launching and tracking space probes.

In contrast, Einstein's insight that space and time are linked—that "space tells matter how to move; matter tells space how to curve"—is crucial to many cosmic phenomena. But it's hard to test a theory whose consequences are so remote. For almost half a century after it was proposed, general relativity was sidelined from the mainstream of physics. But from the 1960s onward, evidence has grown for a "big bang" that set the universe expanding and for black holes—two of Einstein's key predictions.

And in February 2016, nearly a hundred years after the famous Royal Society meeting reporting the eclipse expedition, another announcement—this time at the Press Club in Washington, DC—further vindicated Einstein's theory. This was the detection of gravitational waves by LIGO (Laser Interferometer Gravitational-Wave Observatory). This is the theme of Govert Schilling's book. He has a wonderful story to tell, spanning more than a century.

Einstein envisaged the force of gravity as a "warping" of space. When gravitating objects change their shapes, they generate ripples in space itself. When such a ripple passes the Earth, our local space "jitters": it is alternately stretched and compressed as gravitational waves pass through it. But the effect is tiny. This is because gravity is such a weak force. The gravitational pull between everyday objects is minuscule. If you wave around two dumbbells, you will emit gravitational waves—but with quite infinitesimal power. Even planets orbiting stars, or pairs of stars orbiting each other, don't emit at a detectable level.

Astronomers are agreed that the only sources that LIGO might detect must involve much stronger gravity than in ordinary stars and planets. The best bet is that the events involve black holes. We've known for nearly fifty years that black holes exist: most are the remnants of stars twenty or more times more massive than the Sun. These stars burn brightly, and in their explosive death throes (signaled by a supernova), their inner part collapses to a black hole. The material that the star was made of gets cut off from the rest of the universe, leaving a gravitational imprint on the space it's left.

If two black holes were to form a binary system, they would gradually spiral together. As they get closer, the space around them becomes more distorted until they coalesce into a single, spinning hole.

This hole sloshes and "rings," generating further waves until it settles down as a single, quiescent hole. It is this "chirp"—a shaking of space that speeds up and strengthens until the merger, and then dies away—that LIGO can detect. These cataclysms happen less than once in a million years in our galaxy. But such an event would give a detectable LIGO signal even if it happened a billion light-years away—and there are millions of galaxies closer than that. To detect even the most propitious events requires amazingly sensitive—and very expensive—instruments. In the LIGO detectors, intense laser beams are projected along four-kilometer-long vacuum pipes and reflected from mirrors at each end. By analyzing the light beams, it's possible to detect changes in the distance between the mirrors, which alternately increases and decreases as space expands and contracts. The amplitude of this vibration is exceedingly small, about 0.0000000000001 centimeters—millions of times smaller than the size of a single atom. The LIGO project involves two similar detectors about 3,000 kilometers apart—one in Washington State, the other in Louisiana. A single detector would register microseismic events, passing vehicles, et cetera. To exclude these false alarms, experimenters take note only of events that show up in both.

For years, LIGO detected nothing. But it went through an upgrade, coming fully on line again in September 2015. After literally decades of frustration, the quest succeeded: a chirp was detected that signaled the collision of two black holes more than a billion light-years away, and it opened up a new field of science—probing the dynamics of space itself.

It is sadly not unknown for hyped-up scientific claims to be mistaken or exaggerated—and the book recounts such claims in this field, too. I count myself a hard-to-convince skeptic. But what the LIGO researchers claimed—the culmination of literally decades of effort by scientists and engineers with high credentials—is compelling, and this time I expect to be fully convinced.

This detection is indeed a big deal. It's one of the great discoveries of the decade, up there with the detection of the Higgs particle, which caused huge razzmatazz in 2012. The Higgs particle was a capstone to the Standard Model of particle physics, developed over several decades. Likewise, gravitational waves—vibrations in the fabric of space itself—are a crucial and distinctive consequence of Einstein's theory of general relativity.

Peter Higgs predicted his particle fifty years ago, but its detection—and the pinning down of its properties—had to await the march of technology. It required a huge machine, the Large Hadron Collider in Geneva. Gravitational waves were predicted even earlier, but detection has been delayed because the quest involves detecting a very elusive effect and again requires large-scale and ultra-precise equipment.

Quite apart from offering a completely new vindication of Einstein's theory, these results deepen our understanding of stars and galaxies. Astronomical evidence on black holes and massive stars is limited—it was hard to predict how many would be within range. Pessimists thought that the events might be so rare that even the new and improved LIGO wouldn't detect anything, at least for a year or two. But unless the experimenters have had exceptional "beginners' luck," it looks as though a new kind of astronomy has been founded, revealing the dynamics of space itself rather than the material that pervades it. Other detectors in Europe, India, and Japan have been included in the search, and there are plans to launch detectors into space.

But all too many scientists shy away from trying to explain their ideas and discoveries, believing that they're arcane and incomprehensible. It's true that professional scientists express their ideas via mathematics—a foreign language to many people. But the key ideas can be expressed in simple language by sufficiently skilled writers. Govert Schilling is one of the best of these, and he has surpassed himself in this book. His narrative spans more than a century. The book explains the key concepts in clear and entertaining terms, setting them in historical context. He also depicts the diverse personalities involved. Some have been "obsessives," but this is unsurprising—indeed obsessiveness is a prerequisite for anyone devoting years, even decades, to an experimental challenge with no guarantee of any payoff. But the effort has been supported by hundreds of experts cooperating in teams. He tells of boisterous controversies, setbacks, and amazing technical achievements by scientists and engineers who struggled for decades to achieve fantastic precision. He relates how they emerged triumphant, revealing clues to the bedrock nature of space and time. It is a wonderful story, engagingly and rivetingly told.

Contents

Introduction

Orbiting a yellow dwarf star on the outskirts of a spiral galaxy is a tiny planet formed some 3.3 billion years ago from accumulating dust and pebbles. Organic compounds that rained down from outer space into the blue planet's lukewarm oceans have arranged themselves into self-replicating molecules. By now, those waters are brimming with single-celled life-forms. It won't be too long before life finds its way onto the planet's barren continents.

In another corner of this vast universe, two extremely massive stars have ended their brief lives in catastrophic supernova explosions. What's left is a tight binary of voracious black holes, each tens of times more massive than the faraway yellow dwarf star. Their gravity pulls in gas and dust that venture too close, and bends the paths of light rays in their vicinity. Nothing will ever be able to escape the tight gravitational grip of these cosmic abysses.

As the black holes orbit each other, they're making waves: minute ripples in spacetime that propagate with the speed of light. The waves carry away energy, causing the two holes to draw closer and closer. Eventually they orbit each other hundreds of times per second at half the speed of light. Spacetime is stretched and squeezed; the tiny perturbations grow into massive waves. Then, in a final burst of pure energy, the two black holes collide and merge into one. Quiet returns to the scene. But the last powerful waves are spreading into space like a tsunami.

It takes the death cry of the two black holes 1.3 billion years to reach the outskirts of our spiral galaxy. By then, their amplitude has diminished tremendously. They still push and pull on everything that's in their way, but nobody would ever notice. On the blue planet, ferns and trees now cover the surface; an asteroid impact has wiped out giant reptiles, and one of the many lines of mammals living on this world has evolved into a species of curious two-legged creatures.

Having passed the outer regions of the Milky Way galaxy, the gravitational waves from the distant black hole merger take only 100,000 years or so to reach the vicinity of the Sun and the Earth. As they race toward the planet at 300,000 kilometers per second, people start to explore the universe they're part of. They grind telescope lenses, discover new planets and moons, and map the Milky Way.

One hundred years before the waves arrive—they've covered 99.99999 percent of their 1.3-billion-light-year trip—a twenty-six-year-old scientist named Albert Einstein predicts their potential existence. It takes another half century before people seriously start to hunt them down. Finally, in the early twenty-first century, detectors have become sensitive enough. Just a few days after being switched on, they register the tiny vibrations, much smaller in amplitude than the size of an atomic nucleus.

On Monday, September 14, 2015, at 09:50:45 Universal Time, a hundred-year-old prediction of Einstein is borne out as astronomers secure a gravitational message from a black hole collision in a galaxy far, far away.

The first direct detection of a gravitational wave is rightly hailed as one of the greatest scientific discoveries of the new century. Further detections, with ever more sensitive equipment, will provide astronomers with a completely new way of studying the violent universe and offer physicists the opportunity to finally solve the secrets of spacetime.

A few years before the latest version of the Laser Interferometer Gravitational-Wave Observatory (LIGO) went online, I first thought about writing this book. Wouldn't it be great, I thought, if the first observation of a gravitational wave took place right around the time