ADVANCED GRAVITATIONAL WAVE DETECTORS

After decades of research, physicists now know how to detect Einstein's gravitational waves. Advanced gravitational wave detectors, the most sensitive instruments ever created, will be almost certain to detect the births of black holes throughout the Universe. This book describes the physics of gravitational waves and their detectors.

The book begins by introducing the physics of gravitational wave detection and the likely sources of detectable waves. Case studies on the first generation of large-scale gravitational wave detectors introduce the technology and set the scene for a review of the experimental issues in creating advanced detectors in which the instrument's sensitivity is limited by Heisenberg's Uncertainty Principle. The book covers lasers, thermal noise, vibration isolation, interferometer control and stabilisation against opto-acoustic instabilities. This is a valuable reference for graduate student and researchers in physics and astrophysics entering this field.

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"This book is not only a monograph on advanced gravitational wave detectors and the astrophysical phenomena they will explore, it also contains a pedagogically fine introduction to the field of gravitational wave science. I recommend it to any budding or mature scientist or engineer who wants an overview of this exciting field and where it is going."

Kip. S. Thorne, Feynman Professor of Theoretical Physics, Emeritus, Caltech

"Almost 100 years after Einstein introduced his Theory of General Relativity, we are finally on the threshold of making direct detections of gravitational waves ... *Advanced Gravitational Wave Detectors* gives us an up-to-date view of the science and techniques for making the first detections and then developing yet more sensitive future detectors ... This comprehensive review, written by experts in gravitational waves physics, covers these topics in depth and will serve as a very good introduction for students, while at the same time, being a valuable resource for practitioners in the field."

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Cover illustration (front): Simulation of two neutron stars merging into a single hypermassive neutron star. This will collapse to produce a black hole after a fraction of a second. High density is represented by green through to low density represented by orange. The low-density (orange) material will produce a torus orbiting the black hole, the possible configuration behind gamma-ray bursts. Credit: Ralf Kähler (Max Planck Institute for Gravitational Physics/Zuse Institute Berlin); based on work presented in Baiotti, Giacomazzo, and Rezzolla, *Phys. Rev. D*, **78**, 084033 (2008)); (back, left): aerial view of Virgo, the Italian/French gravitational wave detector. The detector Virgo is located in the countryside of Commune of Cascina, a few kilometres south of the city of Pisa, Tuscany. Credit: image courtesy of the Virgo Collaboration; (back, right): view of the GEO 600 building showing a squeezed light source surrounded by several vacuum chambers containing suspended interferometer optics. Credit: photo taken by Hartmut Grote of the Max-Planck-Institute for Gravitational Physics.

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In memory of Stefano Braccini, our co-author and respected colleague.

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Foreword

In 1905, Albert Einstein published a series of papers that revolutionised physics. They demonstrated the existence of molecules as physical entities, started the thinking that led to quantum mechanics, and laid the foundations of Special Relativity. Einstein then spent the next decade developing his Theory of General Relativity – a work that arguably was his greatest achievement. A key feature of general relativity was the prediction of the existence of gravitational waves. More generally, this new theory of gravity has come to be universally recognised as giving our best description of the Universe.

Now, almost 100 years after Einstein introduced his theory, we are finally on the threshold of making direct detections of gravitational waves. This greatly anticipated achievement will enable us to make rigorous tests of general relativity, as well as give us a completely new way to view the Universe.

Advanced Gravitational Wave Detectors, gives us an up-to-date view of the science and techniques for making the first detections and then developing yet more sensitive future detectors. There are many ingenious ideas and advanced technologies incorporated into the large-scale instruments that are poised to detect gravitational waves. The detections will come from neutron stars, black holes or other such objects that were unknown in Einstein's time. The techniques will involve lasers, photodiodes and digital data acquisition systems, also unknown at that time.This comprehensive review, written by experts in gravitational waves physics, covers these topics in depth and will serve as a very good introduction for students, while at the same time, being a valuable resource for practitioners in the field.

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Preface

The detection of gravitational waves is sometimes described as the Holy Grail of Modern Physics. This is somewhat of a misnomer. Like the search for the holy grail, the search has appeared endless and fruitless, especially to non-scientific observers who cannot believe that it could take so long to make a detector, test it and come up with a firm answer. But unlike the search for the holy grail, physicists *know* that gravitational waves exist, not only from the beauty and elegance of Einstein's General Theory which predicts their existence, but also from the observations of binary pulsar systems which lose energy exactly in accordance with the theoretical predictions. This work by Joseph Taylor was rewarded with the 1993 Nobel Prize in physics.

The saga of gravitational wave detection goes back a long way: Einstein believed they existed but thought they were not physically detectable. Eddington queried their existence: he suggested that 'they travel at the speed of thought'. But in the 1950's Pirani, Feynman, Bondi and later Isaacson proved their physical reality, and in about 1960 Joseph Weber began to develop his famous resonant mass detectors. One now resides in the Smithsonian museum and another at one of LIGO's gravitational wave observatories. About 1970 his claims of detection (which turned out to be false) fired up a whole community. Astronomers were the most skeptical of Weber's results because they implied that thousands of stellar masses of matter were being turned into gravitational waves in the Milky Way every year. Weber's claims alerted physicists to the challenge and the possibility of detecting gravitational waves. A concentrated effort began, both to repeat his results, and to design vastly better detectors.

By 1975 there was a consensus that Weber's results were false. By this time a programme to build cryogenic versions of Weber's detectors was well underway, in the USA and Italy and a few years later in Australia. Cryogenic techniques and superconducting sensors offered at least a million-fold improvement in energy sensitivity to sharp bursts of gravity waves emanating from supernovae and neutron star births. At the time it appeared relatively straightforward to lower the detector temperatures to a degree or so above absolute zero, enabling the use of new superconducting vibration transducers, and simultaneously reducing thermal acoustic noise until vibrations as small as 10^{-20} metres could be detected, corresponding to gravitational wave strains in the 10^{-21} range.

The difficulty in creating cryogenic detectors was seriously underestimated. A whole range of new technologies had to be integrated, from ultra-low acoustic loss materials to new superconducting vibration sensors and amplifiers, to vibration isolation at a level never before encountered. There were numerous setbacks, including the vacuum implosion of one cryostat and the earthquake destruction of the detector at Stanford.

Only in the 1990s did five cryogenic detectors come into long-term operation. They set definitive limits on the strength and rate of gravitational wave bursts, and firmly disproved earlier claims. But even at vastly improved sensitivity, no signals were detected. This was not really a surprise since by this time likely sources were better understood and the bursts to which these detectors were most sensitive to were likely to be very rare – say once every century.

The detector builder's optimism had been sustained by the hope that there may have been a class of unknown sources waiting to be detected. The hope was dashed! Still, the resonant mass detectors set important upper limits which were not to be broken until an entirely new technology became operational in the first decade of the 21st century.

The detection of gravitational waves with laser interferometers was first considered in the 1960s, with experiments beginning in Europe and the USA in the 1970s and 1980s. There was a long period of setbacks and innovation as entirely new technologies were developed. Finally in the 1990s huge laser interferometer instruments began construction in USA (the LIGO project), in Italy (the French–Italian Virgo project), in Germany (the British–German GEO project) and in Japan (the TAMA project). These detectors have broad bandwidth, and are particularly designed to detect the final stages of the coalescence of neutron stars. In their last seconds such systems create rapidly rising chirp signals as the stars sweep around each other at up to 500 times per second.

Once built, the detectors took a massive effort as physicists learnt how to bring them into sensitive operation, but by 2009 the detectors had operated for long periods of time, and greatly exceeded all previous limits. Again, no signals were detected, but this time the limits began to place significant constraints on the astrophysics of sources.

The next step in the saga will take us well into the second decade of the 21st century, and will bring about, for the first time, detectors capable of detecting known gravitational wave sources at a frequent rate. Many years before they demonstrated that their detectors worked in accordance with predictions, the growing band of gravitational wave physicists had embarked on a worldwide collaboration to develop designs for detectors that would be able to reach reach into the Universe at least 10 times further than the first laser interferometers. Such detectors are known as 'advanced' detectors. The keys to the advances required are extremely high laser power, massive mirrors and new concepts in interferometer design. The physics of the detectors is presented here. At the frontier of knowledge there is room for new difficulties, but as I write there is a feeling that gravitational wave detection in imminent.

It is impossible to guess when the saga of gravity wave detection will end. While advanced detectors are constructed the next generation of third generation detectors is being planned. The field remains fascinating and intensely innovative. The next detectors will exceed the standard quantum measurement limit, and avoid the effects of classical environmental gravity gradient forces.

There appears no doubt that gravitational astronomy will give us a new sense. It will allow humanity to explore the beginning of time in the Big Bang, and the end of time in black holes. It will allow us to observe the most energetic events in the Universe through the detection of vibrations so tiny that 50 years ago they were beyond our imagination. Gravitational wave detectors will listen in to most of the visible Universe, making a census of the dark side of the Universe: black hole births, and stellar deaths. This book, written by experts in the field, introduces you to the physics of this exciting new field.

David G. Blair

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Introduction

By late 2010 five large-scale laser interferometer gravitational wave detectors had been operating for several years at unprecedented sensitivity. They were searching for gravitational wave signals created by matter in its most extreme and exotic form – neutron stars, black holes and the Big Bang itself. The detectors were the most sensitive instruments ever created, able to detect fractional changes in spacetime geometry at the level of parts in 10^{23}, corresponding to the measurement of energy changes of less than 10^{-31} joules per hertz of bandwidth. Despite this extraordinary achievement, the sensitivity was about 10 times below the level where we could be confident of detecting predicted signals. For example, the mean time between detectable chirp signals from the coalescence of pairs of neutron stars was likely to be once every 50 years, so that in a year of operation the chance of detection was only about 2%.

Despite this pessimistic prognosis, many of the 1000 physicists in the worldwide collaborations involved with the above detectors remained optimistic that nature might to kind enough to provide a first signal. Optimism was high enough that a system had been put in place to alert optical telescopes to slew to the part of the sky corresponding to the arrival times of any significant event.

On 16 September 2010 a coincident signal appeared in LIGO detectors spaced 2000 kilometres apart in the USA. It was immediately recognised as a significant event, especially after it was also identified in the data of the Virgo detector in Italy. By triangulation of the arrival times, it was determined to have come from the direction of the constellation Canis Major, the Big Dog. Within minutes telescopes in Australia, France and Chile and in orbit had been automatically alerted and many images of the region of the sky were taken. The signal appeared to have come from a coalescing pair of black holes at a distance of order 100 million light years. The absence of an optical signal was not surprising.

Members of the collaborations were soon alerted, but we were all required to keep the event secret until two things had happened. First, the data needed to have been fully analysed and all possible ways that the signal could be a false positive needed to be considered. Second, we had to wait until the *blind injection* envelope was opened. We were reminded that we had agreed to the process of blind injections. In this process rare events *might* be injected into the detectors to test the ability of the detectors to distinguish between real signals and accidental glitches in the data.

It took many months to complete the data analysis. More than 100 scientists were involved in the data analysis. Groups pored over data channels searching for possible electrical, optical or acoustic interference. Different search algorithms were tested and compared. Eventually it was determined that the probability that the event was accidental was one in 7000 years. A paper announcing the first discovery of gravitational waves was written. Finally, on 14 March 2011, the collaboration met in Arcadia, California, where the blind injection envelope was to be opened.

A large lecture hall equipped with six data projectors was packed and more than 100 scientists all over the planet were present via internet connection. First, a series of presentations presented the scientific case for discovery of gravitational waves from a coalescing pair of black holes. People took bets on the event being real. Most people agreed that it was 99% certain to be an injection, and yet the tension and the suspense was palpable. A leading member of the collaboration declared that he was sure the event was real. Champagne glasses were brought out, and filled, and a thumb drive was handed to Jay Marx, director of LIGO. He plugged it in. A presentation appeared on all six screens entitled 'The Envelope'. One click and we had the answer: it was a blind injection! Still, we drank our champagne because this was really a triumph. The effort had proved that these enormously complex instruments could detect single rare events, and determine their nature. Rather than toasting to the discovery of gravitational waves, we toasted to Advanced LIGO, the detector that would mark the beginning of gravitational wave astronomy in about 2015, along with Advanced Virgo, LCGT in Japan, and hopefully an Australian detector.

As we write, gravitational waves have still not been detected. The LIGO detectors are being rebuilt to create the first *advanced* detectors. Later the Virgo detector will shut down for its upgrade. The GEO high frequency detector in Germany and two resonant mass gravitational wave detectors in Italy will continue to listen for a rare and strong event that could occur any time in our galaxy.

This book is designed to help train the young scientists who will be the explorers of the gravitational wave spectrum. The first chapters are intended for a general scientific audience, and for undergraduate level students. Here we discuss the breadth of gravitational wave spectrum, and proposed methods for exploring the spectrum, as well as the exquisite new technologies that make the exploration possible. Later chapters specialise on the different technical topics that combine to cover the entire field of ground-based interferometric gravitational wave detectors. This part is designed for advanced students and researchers in the field. Many of the chapters contain new and previously unpublished results.

All the authors of this book are members of the large international collaborations mentioned above. All the chapters were peer reviewed through the LIGO Scientific Collaboration. We are all grateful to the collaboration for this process which helped to ensure the quality and the accuracy of all the chapters. Additionally, we would like to thank and acknowledge Luciano Rezzolla and Anthony Mezzacappa for providing valuable insight on state-of-the-art simulations of gravitational wave burst sources. On behalf of all the authors we thank all our colleagues who helped and contributed to the work presented in this book.

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