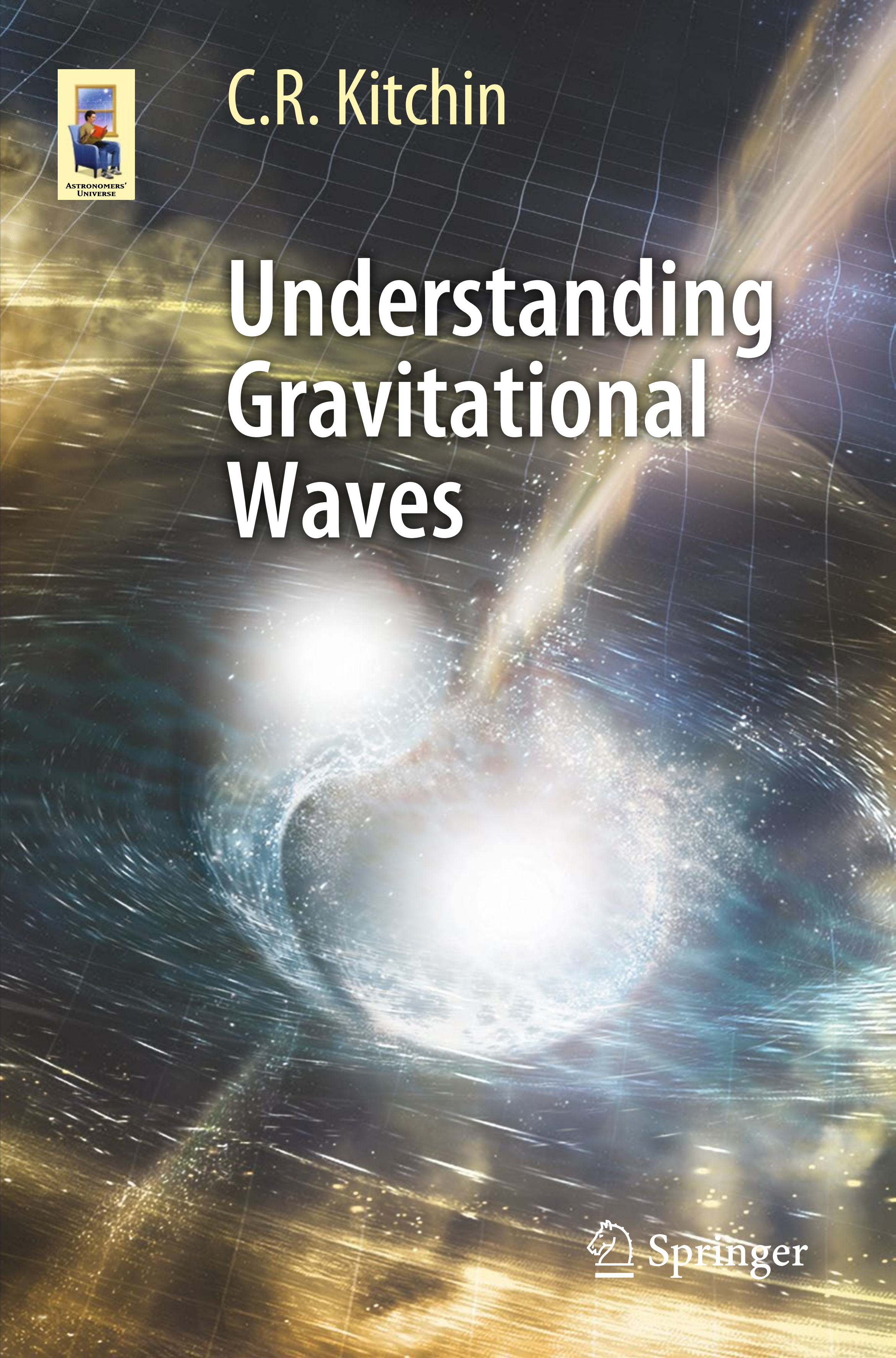
Astronomers' Universe

C.R. Kitchin

Understanding Gravitational Waves



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Astronomers' Universe

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C. R. Kitchin
University of Hertfordshire
Hatfield, Hertfordshire, UK

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Cover Image: Artist's illustration of two merging neutron stars. The rippling space-time grid represents gravitational waves that travel out from the collision, while the narrow beams show the bursts of gamma rays that are shot out just seconds after the gravitational waves.

Credit: NSF/LIGO/Sonoma State University/A. Simonnet

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For
Christine,
Willow,
Lottie and Arthur
and in treasured memory of
Rowan

Preface

> Physics is essentially a concrete and descriptive science. The mathematics gives us only the means in hand to express the law according to which the phenomena are taking place. (Albert Einstein. 'Lettres à Maurice Solovine'. Gauthier-Villars, 1956)

There it is—Einstein himself said it—Physics is a descriptive subject—Maths is just a means to an end.

So, when you open most other books or articles trying to tell you about gravity and gravitational waves, why are you faced with page after page filled with equation after equation, with maybe just the odd word or two here and there?

That is because to astronomers, astrophysicists and physicists, mathematics is their shorthand—they can describe things quicker using it, than if they were to use plain language.

However, just as a shorthand typist transcribes the squiggles of shorthand into plain language, so the squiggles of mathematics can also be transcribed into plain language. As Einstein may also have said: 'You do not really understand something until you can explain it to your grandmother. ' (Widely, but not reliably, attributed to Albert Einstein).

Thus, the objective of this book is to explain the natures of gravitational waves; what they are, why they are so significant, where they come from and why nobody has noticed them before now—to all grandmothers—and also to all grandfathers, mothers, fathers, children, grandchildren, aunts, uncles, sisters, brothers, nieces, nephews, cousins, … everywhere, using just plain language—or to express this more plainly; just using words. There are no equations in this book with which you have to wrestle.

Describing gravitational waves in plain language, though, does not mean that the ideas and concepts being described will be easy to comprehend. In reading this book, you will need to concentrate, work and think carefully about those ideas and concepts even though, or perhaps especially because, they are expressed non-mathematically. As Einstein said—and third time pays for all:

> A hundred times every day I remind myself that … I must exert myself in order to give in the same measure as I have received and am receiving (Albert Einstein. 'The world as I see it'. Forum and Century, Volume 84, 1930).

All that said—I hope you find this book wonderful in the literal sense, illuminating, interesting and informative and I have no doubt at all that you will find that:

> … the Universe is not only queerer than we suppose, but queerer than we can suppose. (John B.S Haldane. 'Possible Worlds and Other Essays'. Chatto & Windus, 1927).

Hatfield, Hertfordshire, UK C. R. Kitchin
January 2021

Read This Before You Jump-in at the Deep End

How to Read This Book

The readership for this book may range from people who have vaguely heard of gravitational waves somewhere or other and now want to know a little more, to amateur and even professional astronomers and astrophysicists whose specialisms lie elsewhere than with gravitational waves. To enable all such readers to use the book profitably, it is written with its main theme as the backbone, together with separate tutorials which provide additional information for when it may be needed.

It is unlikely that all readers will need to look at all tutorials and many readers may prefer to skip the tutorials on a first run-through, coming back to them afterwards or at a point where they find they do need that information after all.

The tutorials are at three levels:

- Memory Refreshers—for reminding readers about material which they have probably encountered previously
- Further study—for topics which are needed, but which are probably new to most readers and which will probably need to be read-through before proceeding with the main theme of the book
- For the High-Fliers—advanced topics and/or interesting sidetracks which may be safely left until after a first read, unless the topic grabs the reader's interest irresistibly at the instant that it is first encountered.

A guide to the concentration likely to be needed to follow each tutorial is given, rather subjectively, via the use of stars:

- ☆—should be fairly straight-forward
- ☆☆—don't have the TV on at the same time that you're reading this
- ☆☆☆—open a bottle of champagne when you've successfully got this one.

Most of the tutorials are to be found in the Appendices:

- Appendix A—Memory Refreshers
- Appendix B—Further Study
- Appendix C—For the High Fliers.

Additionally, though, some short asides are placed in boxes within the main text, to be perused or not as wished.

Numbers

The objective of this book, then, is to explain gravitational waves and the properties of gravity itself which underlie the waves, in plain language.

However, Astronomy is Astronomy—and proverbially it deals with Astronomically Large Numbers. With gravitational waves, we will additionally encounter Ultra-Microscopically Small Numbers.

Thus, whilst 'real' mathematics—i.e. equations, formulae, functions, theorems, derivations, etc.—is avoided, actual numbers do have to be used—and occasionally added, subtracted, multiplied or divided.

Ordinary Arabic numbers, such as 1, 2, 3 … 1,000 … 1,000,000 …, or their word equivalents—one, two, three, …, etc., are simply too cumbersome and often too confusing when they become very large or very small. We shall therefore make extensive use of numbers in their index forms, for example, 10^{14} (= 100,000,000,000,000) or 10^{-7} (= 0.000 000 1). Readers for whom the index notation for numbers was encountered more years ago than they care to remember, will find a guide to them in Appendix ☆ A.1.

Units

The units of commonly encountered quantities, such as time or distance, are likely to be familiar to most readers, being seconds or metres, etc. Of course, things can get more complicated with compound quantities, such as velocity or acceleration, while for some quantities, for example, the gravitational constant, the units can start to look like quite involved equations. You should, however, take due note of Arthur Dent's heart-felt cry:

> "I like the cover," he said. "DON'T PANIC. It's the first helpful or intelligent thing anybody's said to me all day." (Douglas Adams, 'Hitchhiker's Guide to the Galaxy'. BBC Radio 4, 1978)

Thus, fortunately, whilst it is necessary for accuracy and clarity to include the units in this book when quoting values of quantities, most of the time you can just gloss over them.

The index notation for units, then, is generally used throughout the book in writing-out the units of quantities. The units of velocity, for example, metres per second, are thus shown as m s^{-1}. A fuller explanation of this usage may be found in the Appendix ☆ A.2.

Constants, Definitions, Quantities, Symbols and Units

Selected values and explanations of frequently used constants, quantities, definitions and symbols are listed in Appendix D. This book utilises the *Système international d'unités*, or SI system, so that units of force, for example, are newtons (N) and the units of energy are joules (J). Appendix D provides details of the SI system and units and also of some non-SI units, such as parsecs, which are widely used in astronomy. Readers requiring further explanations, information and/or conversion factors to other unit types not included in Appendix D, will easily find them via a quick internet search, or within most physics books.

Topicality

With the third observing run of the AdvLIGO and AdvVirgo (Advanced Laser Interferometer Gravitational Wave Observatory, Advanced Virgo—Figure 1.1) brought to an end by the Covid-19 pandemic in March 2020, we now have a total of 78 events to study (Chapter 6)—and these include the mergers of black holes with masses millions of times that of our little Earth, spectacular collisions of two neutron stars and neutron stars falling into black holes. This book is up-to-date with these observations and other material to the beginning of 2021. Sufficient is now known, though, about the main types of gravitational wave events that, while surprises are undoubtedly still in store for us in the future, the majority of those events will be understandable on the basis of our now existing knowledge—and that is what you will encounter throughout the rest of this book.

Contents

1

14th September 2015

A Date that will be in the History Books, Centuries from now

<table>
<tr><th>Timeline 1.1—Radio Waves</th><th>Timeline 1.2—Gravitational Waves</th></tr>
<tr><td>1864—Maxwell rigorously predicts the existence of radio waves</td><td>1960—Trautman and Robinson rigorously predict the existence of gravitational waves</td></tr>
<tr><td>1886—Heinrich Hertz produces and detects radio waves</td><td>2015—Rainer Weiss and many others detect gravitational waves</td></tr>
<tr><td rowspan="2">2020—Most people on Earth use applications of radio wave technology—communications, the internet, GPS, Wi Fi, remote controls, mobile phones, television, radio, contactless payments, radar, radio astronomy, and so on—many depend upon it for their livelihoods and modes of living and some depend upon it for their lives</td><td>2150?—Most people on Earth use applications of gravitational wave technology …</td></tr>
<tr><td>The rest of this statement is left for the reader to complete—but be assured that your wildest imaginings will fall far short of the reality—Hertz, himself, is reported as saying about his discovery of radio waves ‘It is of no use whatsoever …’</td></tr>
</table>

These two brief timelines will serve, I hope, to highlight the sheer magnitude of what happened on the 14th of September 2015. It was not just another over-hyperbolae-ed scientific discovery, to be forgotten when the next advert for toothpaste comes on—it was something that within some peoples’ lifetimes today could be influencing the lives of all people who are then on or off our planet.

Of course, there are some important differences between the two scenarios—radio waves, in their essence, are identical to light, infrared,

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ultraviolet, X-rays, gamma rays, microwaves, etc.; all being forms of electromagnetic radiation. These different forms of electromagnetic radiation interact with matter in different ways—and that is why we humans find so many different and useful applications for them and why they tell us so much about the Universe, but all forms are identical in their basic natures.

Gravitational waves are totally different from electromagnetic waves, they originate via quite different physical mechanisms and interact, or do not interact, with matter in completely different fashions—the Sun, for example, is more-or-less transparent to gravitational waves, so that we could, potentially, observe what is happening behind it.

We may thus expect to get completely new perspectives about the nature of the Universe through the study of gravitational waves and, if we can start to control and/or generate them, then we may develop applications which may make present-day science fiction authors' most absurd speculations look quite modest (Chapter 9).

On the down side, we should note that the apparatus used by Hertz could have been purchased, in his day, for much less than the then average yearly wage. Weiss' AdvLIGO and the other gravitational wave detectors (Chapter 8) each cost around 10,000–100,000 times an average year's wage today. Also, Hertz produced as well as detected radio waves—we have yet to produce gravitational waves which we can also detect, and it is likely to be some time before we can do so.

Question: So, what was it that happened that was of such significance on the 14th of September 2015?

Answer: The two instruments forming the AdvLIGO (Chapter 8) gravitational wave detectors made their first detections and the first detections ever of a gravitational wave by humankind.

What AdvLIGO found was a burst of gravitational waves lasting for about a third of a second, starting at a frequency of 35 Hz and shooting up to 250 Hz.

As it was a Gravitational Wave and it was detected in 2015 on September the 14th, the event was given the official name:

GW150914

Throughout the rest of this book, though, the gravitational wave event names will be prefixed by a simple running number, as in:

{10} GW150914

in the hope of improving clarity and memorability and as described further in Box ☆ 1.1.

Box ☆ 1.1: Terminology

This way of naming transient astronomical events, by using a code for the type of event, plus the date of its observation or discovery, is a fairly common system nowadays. Gamma Ray Bursters, for example, have names such as GRB200219A and GRB200219C for the two bursts that were observed on the 19th of February 2020.

Gravitational wave events also occasionally occur more than once a day, so from 2019 onwards, they have had letters added to their names. Thus, there have recently been GW190930s and GW190930t which were observed at 13 35 UTC and 14 34 UTC, respectively, on the 30th of September 2019.

The 's' and 't' indicate that these two events were the 19th and 20th alerts, of any type, which had occurred with the gravitational wave detectors on that day. The alerts 190930a to 190930r and those from 190930u onwards all turned out to be due to non-gravitational-wave causes.

The 27th alert of the day is given a double letter, starting at 'aa' and followed by 'ab', 'ac' and so on. Thus, we have GW200106av; the 48th event of the 6th of January 2020, and the only one that day to be thought to have arisen from a gravitational event. During the third LIGO/Virgo observing run (O3), the actual time of an event's detection has sometimes been used in place of these final lower case letter(s). Thus, **{120}** GW190408an occurred at 18h 18 m 2 s UTC, so it may also be encountered elsewhere as GW190408_181802.

Prior to final analysis of the event, the prefix 'S' is used in place of 'GW'—however, in this book, for simplicity, 'GW' is used as the prefix for all the recognised gravitational wave events.

Now, you have probably already found it difficult to remember and distinguish between these 'names'. As an aide-memoire, therefore, throughout this book, a simple running number is added to the official designations. This is shown in bold and in curly-brackets, starting at **{10}** and going up in tens; **{10}**, **{20}**, **{30}**, etc.—the reason for the progression in tens is to allow for the later insertion events identified as being real, but only months or years after their occurrence—although there are no such usages in the book at the time of writing.

Thus, the first gravitation wave event will, hereinafter, be called:

{10} GW150914

and you only need to remember the **{10}**, not the 'GW150914'. When several gravitation wave events are being discussed as in, say

> ' … binary neutron star mergers **{90}** GW170817, **{610}** GW191213g and **{180}** GW190425z are … ',

then they should be easier both to remember and to relate to each other using the curly-bracket identifications.

You may also find it easier to relate to the events by knowing in which of AdvLIGO/AdvVirgo's three observing runs they were found;

2015—Run O1—Events **{10}** GW150914 to **{30}** GW151226
2017—Run O2—Events **{40}** GW170104 to **{110}** GW170823
2019 to 2020—Run O3—Events **{120}** GW190408an to **{780}** GW200316bj

So, to repeat the earlier question: just 'what was it that happened on the 14th of September 2015?'—and what are the 'the two instruments forming the AdvLIGO (Chapter 8) gravitational wave detectors?'

Modern gravitational wave detectors are machines, kilometres across, operated by hundreds of highly qualified scientists and engineers, costing hundreds of millions, if not billions, of US dollars, and they detect collisions between black holes tens of times more massive than our Sun which occurred millions or billions of years ago and halfway towards the edge of the Universe. These instruments are described in detail in Chapters 7 and 8.

From the early 1960s onwards, many types of gravitational wave detectors, including the earlier versions of AdvLIGO, had been in operation (Chapter 7)—with a clear, consistent and total lack of success.

However, after more than half a century, at 9 minutes to ten UTC on that Monday morning in mid-September 2015, a detector's needle finally moved off zero for real; 6.9 milli-seconds later and 3,002 km away, a second detector's needle also quivered—and a completely new branch of science was born. AdvLIGO Livingston is sited in Louisiana and AdvLIGO Hanford is in Washington State—and 3,002 km is the straight-line distance between the two instruments (Figure 1.1).

Actually, **{10}** GW150914 caused some mirrors to move very slightly rather than needles on gauges to move away from zero—but the principle is the same. Inside the two gravitational wave detectors then working—AdvLIGO Livingston and AdvLIGO Hanford (Chapter 8)—eight mirrors chirped for a few milli-seconds at tones rising from about 35 Hz; the second-from-the-left black note on a regular piano keyboard or $C^{\#}1$, to about 250 Hz; the 23rd white note or B3 (Figure 1.2).

Figure 1.1 AdvLIGO Livingston and AdvLIGO Hanford—(Reproduced by courtesy of Caltech/MIT/LIGO Laboratory)

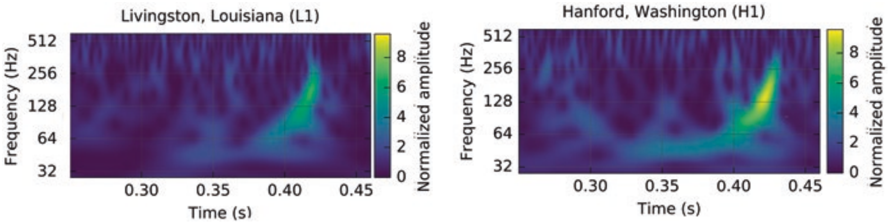

Figure 1.2 The detections of {10} GW150914 by AdvLIGO—Livingston (left) and Hanford (right). The varying strength of the signal is shown by its relative brightness within the image and is labelled as 'Normalised Amplitude' on the right. (Reproduced by courtesy of B.P. Abbott *et al*, '*Observation of Gravitational Waves from a Binary Black Hole*'. Phys. Rev. Lett. 061102-1, **116**, 2016. DOI:https://doi.org/10.1103/PhysRevLett.116.061102)

However, none of the people working the detectors heard those chirps—firstly, because the mirrors were inside gigantic vacuum tubes, so sound waves could not have been formed and secondly, because the maximum movement of any of the mirrors was about four atto-metres.

Now an atto-metre is a very small distance indeed—to paraphrase a well-known quote from Douglas Adams:

> Atto-metres are small. Really small. You just won't believe how vastly, hugely, mind-bogglingly small they are. I mean, you may think the eye of a needle is small, but that's just peanuts to an atto-metre. (Douglas Adams. In original form in 'Hitchhiker's Guide to the Galaxy'. BBC Radio 4, 1978)

In fact, 4 atto-metres is not merely smaller than the eye of a needle, it is not just smaller than an atom, it is not just a bit smaller than an atom's nucleus—itself 100,000 times smaller than the atom—it is a lot smaller than an atom's nucleus—in fact, just 0.25% of the size of a proton or a neutron, the constituent particles of nuclei.

Therefore, even if the gravitational wave detectors' mirrors had not been in hard vacua, no one could have heard their chirps because the mirrors' four atto-metre movements were about 10^{-18} times too small to produce audible 35–250 Hz sound waves.

On the Significance of 1/400 of a Proton's Diameter

Now sub-atomic particles, such as electrons, neutrons and protons, are fuzzy sorts of objects whose apparent sizes depend upon how you try to measure them. Nonetheless, for protons, a fairly useful estimate is that they are about

1.6–1.8 femto-metres in diameter; that is, 1,600–1,800 atto-metres. The four atto-metre movements of the mirrors in the gravitational wave detectors mentioned in the previous section are thus about 1/400 of the diameter of a proton—not very much at all, you may be thinking, for it to be remembered and celebrated centuries from now.

The gravitational wave detectors, though, do amplify that movement, by reflecting light beams many times between the mirrors. The mirrors operate in pairs, separated, for these first detectors, by about 4 km, but the light beams, after being reflected between the mirrors about 280 times, travel about 1,100 km. The mirrors' movements are thus amplified by about a factor of 280—to some 1,100 atto-metres, or about 70% of the size of the proton. Peanuts—if you are a sub-atomic physicist—but 70% of a proton is still pretty tiny by our every-day standards. So, where does its significance lie?

The answer is that these minuscule changes within two instruments on the Earth originated in an event which, for a fraction of a second, produced five times more energy than the whole of the rest of the Universe put together—and the whole of the rest of the Universe put together amounts to nearly 10^{23} stars like our Sun or to 3×10^{28} planets like our Earth—and some estimates suggest that the Universe could even be 20 or so times more massive than that.

The reason why such a mind-bogglingly enormous cause produced such a mind-bogglingly small effect on the Earth is simply distance.

The event which produced **{10}** GW150914's signal on the Earth occurred around 430 Mpc away from us. Now 430 Mpc is some 1.4×10^9 light years or 1.3×10^{25} m, so the event actually occurred some 1.4×10^9 years ago.

The gravitational wave signal which became **{10}** GW150914 has thus been travelling through space towards us—and, of course, out in all other directions as well—since the middle of the Mesoproterozoic era, when 0.1 mm-sized single celled organisms, called eukaryotes, were just evolving on Earth. The signal had covered about 2/3 of its journey towards us when trilobites swam in Earth's seas but it still had 5% of the distance to go when Tyrannosaurus Rex was feasting on Ankylosaur steaks in what are now Northern Mexico and the Western parts of the U.S.A. and Canada.

That incredible amount of energy from **{10}** GW150914's causal event is thus now spread out over a sphere with an equally inconceivable surface area of 2×10^{18} square parsecs or 2×10^{51} square metres—and its intensity now is thus correspondingly infinitesimally small.

What, Then Caused {10} GW150914?

The first person who could have answered the question posed by the title of this section initially drew breath on Christmas day 1724. The Reverend John Michell was born three years before Isaac Newton's death and, appropriately, just 29 miles North of Woolsthorpe-by-Colsterworth; Isaac Newton's birthplace. Fifty-nine years later Michell started wondering about stars 500 times larger in diameter than the Sun—that is, with masses round 10^8 $M_\odot$—and concluded that the escape velocity from them would equal the speed of light. He called such objects 'Dark Stars' since we would not be able to see their light.

Now, though, we call them Black Holes.

Two hundred and thirty-seven years later and still nobody has ever seen a black hole—because—they are—after all—Black.

Even the much-publicised 2019 'image of M87's black hole' (Figure 1.3) was actually an image of the black hole's shadow.

Figure 1.3 The shadow of the super-massive black hole at the centre of the large elliptical galaxy, M87, in Virgo. (Reproduced by courtesy of the EHT Collaboration)

Our modern understanding of black holes is not so very different from Michell's—take the Sun, compress it into a sphere with a radius of 3 km—and you have an object whose escape velocity equals the velocity of light.

That 3 km radius is called the Sun's Schwarzschild radius—and other masses become black holes when their sizes reach their Schwarzschild radii. The relationship is a simple proportionality, so that a 10 solar-mass body (10 $M_\odot$) has a Schwarzschild radius of 30 km, a 0.1 $M_\odot$ body has a Schwarzschild radius of 0.3 km, and so on. The Earth's Schwarzschild radius would be 9 mm and a typical human being would need to be compressed down to around 0.000 000 1 atto-metres before achieving black hole status. The, probably dubious, pleasure of becoming your own personal black hole, though, would be very fleeting—in about 10^{-11} seconds you might evaporate into γ rays through Hawking radiation (Appendix ☆☆ B.3) or perhaps, in even less time (~10^{-34} seconds), disappear into your own singularity, so achieving even greater notoriety.

The actual existence of black holes within the Universe, nonetheless, is well established even though they have yet to be seen directly (see, however, Box ☆☆ 4.3). The evidence for their existence is based upon the stabilities of objects with masses similar to that of the Sun and higher. Whilst such objects are still generating energy by nucleosynthesis, they are very hot, but composed of more-or-less normal gases in which normal gas pressure balances gravity.

Once the nucleosynthesis reactions come towards their end, normal gas pressure no longer suffices to balance gravity and the stars start to collapse. There are, however, two further significant sources of pressure—that due to electrons and that due to neutrons and additionally, light, or electromagnetic radiation more generally, also exerts a pressure (Appendix ☆ ☆ ☆ C.1).

Thus, for stars with masses less than about 1.4 times that of the Sun, the electron pressure can halt the collapse and the star then becomes a white dwarf (Figure 1.4). Stars with masses between about 1.4 and 2.2 $M_\odot$ will collapse beyond the white dwarf stage and become neutron stars. However, there are no further stable stages—any compact object with a mass above 2.2 $M_\odot$ must either be a black hole or be at some stage in the process of collapsing down to a black hole. The strong X-ray source, Cyg X-1, for example, is a binary system with a hot super-giant star as one component and a compact object its companion (Figure 1.5). The masses of the two components are 20–30 $M_\odot$ for the super-giant and about 15 $M_\odot$ for the compact object. The compact component of Cyg X-1 is thus almost certainly a black hole.

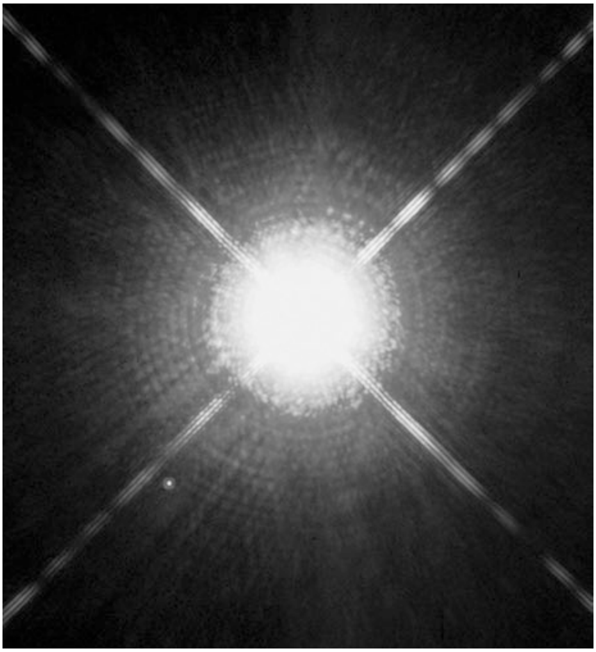

Figure 1.4 An HST image of Sirius (α CMa). Sirius is a binary system with a 2 $M_\odot$ main sequence star (Sirius A) and a 1 $M_\odot$ white dwarf (Sirius B) in mutual orbits. Sirius A is at the centre of the image and is much over-exposed. The diagonal lines are diffraction spikes arising from the telescope's secondary mirror supports. Sirius B is the much smaller dot to the bottom left, but the actual star itself would be about a ten-thousandth of the diameter of that dot on the scale of this image—and about 11,000 km across in reality. It thus has about 300,000 Earth masses squashed into a volume slightly smaller than that of the Earth. (Reproduced by courtesy of NASA, ESA, H. Bond (STScI) and M. Barstow (University of Leicester))

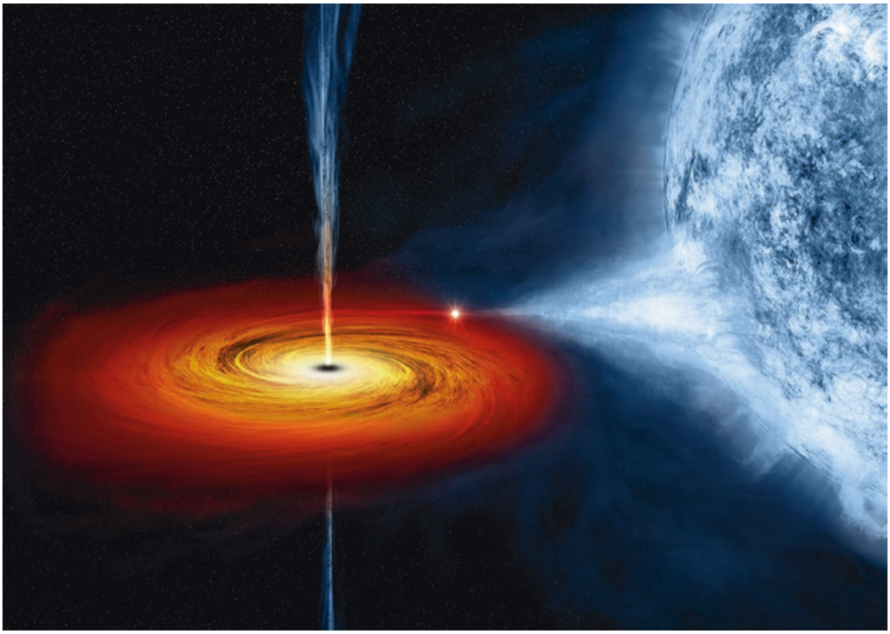

Figure 1.5 Artist's impression of the Cyg X-1 star /black hole binary system. Part of the visible star (HD 226868, 9^m, O-type) is shown on the right of the image. Material is falling from it towards the black hole and goes into an orbiting accretion disk around the black hole. The star-like object on the rim of the accretion disk, where the in-falling matter collides with it, is the hot spot generated by the impact. The black hole is hidden at the centre of the accretion disk and on the scale of this image would be about 100 nm across. Material falling into the black hole generates two relativistic jets which are ejected along the line of the black hole's rotation axis. The approaching jet is shown, the receding jet is red-shifted almost into invisibility. (Reproduced by courtesy of NASA/CXC/M. Weiss)

To return to **{10}** GW150914, many stars, probably more than half, are members of binary, triple, quadruple or higher order multiple star systems. Some 1,400,000,000 years ago, one such binary system was made up from two black holes and the black holes were each at least twice as massive as the one forming a part of Cyg X-1. Our best estimates, in fact, are that they were 31 and 36 $M_{\odot}$, respectively, and so were about 190 and 220 km in diameter.

We do not know how the binary came into existence, nor where the black holes came from, but the two black hole components had probably been much further apart at one time and had been spiralling inwards, getting closer and closer to each other, for a million years or more. We do know that all binary systems radiate gravitational waves continuously, as we shall see later (Figure 5.12) and that their orbits mostly contract as a result.

The energy lost to the binary system depends upon the rate at which the binary's components orbit each other. The orbital periods shorten as the orbits contract and so the gravitational radiation increases—in turn, increasing the rate of contraction and so leading to even higher gravitational energy losses—increasing the contraction rate again—and so on and so on; a runaway-process which can have only one end; the collision and merger of the binary's components.

By the time that the binary black holes were emitting the first detected (35 Hz) part of the **{10}** GW150914 signal, they were less than 2,000 km apart, completing an orbit every 50 milli-seconds or so and moving at speeds close to a third of the speed of light.

Yet they were still closing upon each other and speeding up even further. Within a further quarter or so of a second, they were 'touching' each other (see 'event horizon' Appendix ☆☆ B.3) and merging into a single black hole at mutual speeds close to that of light. The gravitational waves emitted at this instant reached a highest frequency of about 250 Hz.

Two or three milli-seconds later and the two black holes had become a single 63 $M_\odot$ black hole which then oscillated violently for another two or three milli-seconds or so at about 200 Hz.

Then it was all over—or at least things had quietened-down to the point where we could no longer detect the gravitational waves.

You may have noticed that the masses of the two colliding black holes add up to more than that of the single black hole remnant. More precise calculations suggest that the discrepancy is about 3.1 $M_\odot$. That lost mass had been converted into energy during the collision and merger—and because colliding black holes produce gravitational waves very efficiently, that energy was almost all in the form of gravitational waves.

Now the total conversion of even a very small amount of matter produces a vast amount of energy; the average hourly energy consumption by all of humanity is currently around 4.5×10^{16} J—and this could be supplied by the total conversion of just half a kilogram of matter into energy per hour.

3.1 $M_\odot$, however, is 6.2×10^{30} kg of matter, and this was converted during the black holes' merger in just a few tens of milliseconds into 6×10^{47} J of gravitational wave energy. Now if we add up all the electromagnetic energy; gamma rays—light—radio waves, etc., emitted by all the objects in the Universe; ions—atoms—molecules—dust—asteroids—planets—nebulae—stars—galaxies, etc., it amounts, arguably, to around 10^{47} W or 10^{47} J s^{-1}—a quantity called the $L_{Universe}$. **{10}** GW150914's gravitational wave luminosity thus peaked, briefly, at about five or six times the total energy emission of every other object within the entire visible Universe and that is why the mind-bogglingly small movements of the AdvLIGOs' mirrors have caused such excitement.

{10} GW150914 is amongst the stronger gravitational wave signals which we have detected to date, but there will be vastly stronger ones to come and other stronger ones which have occurred in the past. The centres of many galaxies contain black holes massing many millions of $M_\odot$—and some of these super-massive black holes are paired into binary systems. In the galaxy, NGC 6240 (Figure 1.6), there even seems to be a triple system of black holes with masses ranging from 90 million to 700 million $M_\odot$ and their separations ranging from 200 to 1,000 Mpc—and the first collisions between those super-massive black holes could be only a few hundreds of million years off. When, not if, such super-massive systems coalesce, we really will feel the Earth move.

Figure 1.6 NGC 6240 (reproduced by courtesy of NASA, ESA, the Hubble Heritage (STScI/AURA)-ESA/Hubble Collaboration, and A. Evans (University of Virginia, Charlottesville/NRAO/Stony Brook University))

That, however, is a topic to be re-visited when the theoretical background of gravitational waves has been established, the working principles of gravitational wave detectors comprehended and the observations to-date reviewed—and those topics are the subjects for the next few chapters.

2

Gravity: From 850,000,000 BCE to 1915 CE

Few people are capable of expressing with equanimity, opinions that differ from the prejudices of their social environment.
(Albert Einstein. 'Out of my later years'. New York: Philosophical Library, 1950)

From Pre-History to Galileo

Introduction

Gravity is one of the oldest concepts to be found in science, whilst the variations in its properties, known as Gravitational Waves, are amongst the newest. Most of us will have heard of Isaac Newton's falling apple, which prompted him to query why and how such an event could occur.

The answer to Newton's 'why' remains and is likely to continue to remain 'Well that's just the way the Universe is'—or as *Runrig* express it in Calum and Rory Macdonald's song '*The apple came down*':

The apple came down
It had to fall
*
*
The apple must fall
To the ground
(Extract reproduced by kind permission of R. Macdonald).

The answer to Newton's 'how', however, is what is going to take up the rest of this book—as it already takes up a good many other books.

Unless you are a fish—and sadly, the piscean readership of this book is minuscule—you will have experienced weight; that is, the perceptible effect of

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C. R. Kitchin, *Understanding Gravitational Waves*, Astronomers' Universe,
https://doi.org/10.1007/978-3-030-74207-2_2

gravity upon you—from the instant you were born. Prior to that or if you are a fish, your weight would have been counteracted by the buoyancy of the amniotic fluid or water. To most people and to most forms of life going back to the first ones to be able to live on the land, some 850 million years ago, weight is thus just another part of the environment and not to be wondered about.

Newton stands out therefore as being remarkable by simply being inquisitive about gravity at all—but he was not, in fact, the first to speculate about its causes and nature.

In the Beginning

The word 'gravity' itself originates from the Latin 'gravitas' and that in turn from the earlier proto-Indo-European 'gwerə'. So, the origins of the word, 'gravity' may be traced back at least 6,500 years and shows there was an awareness of 'weight' or 'heaviness' amongst the peoples of that time. Almost certainly, though, such a ubiquitous effect must have been thought worthy of its own word soon after the origins of human speech and language. The date of this development is unknown, but Neanderthal man, 450,000 to 40,000 years ago, did, at least, have the physical structures, such as his/her tongue, larynx, etc., sufficiently well developed to enable speech to have occurred—so perhaps some Neanderthal Newton wondered about apples too?

Our earliest real knowledge of someone attempting to quantify weight or heaviness in some manner dates to about 330 BCE when Aristotle argued that heavier objects would fall faster than lighter ones. As far as we know, Aristotle did not conduct any experiments to verify his conjecture: he usually considered experiments to be unnecessary, but even had he done so, it would probably have shown his conjecture to be valid—after all, within the Earth's atmosphere a feather does fall more slowly than a hammer. He also argued that objects fell 'perpendicularly' because they were objects belonging to the Earth group amongst the four classical essences—Air, Earth, Fire and Water—and therefore they attempted to move to their 'natural' place at the centre of the planet Earth.

Suggestions for the correct idea—that heavy and light objects fall at the same rate (Figure 2.1)—were variously made over the two millennia following Aristotle, although in most cases it is not now clear whether or not these were based upon any form of experiment. Thus, John Philoponus in his c. 517 book *Commentary on Aristotle's Physics* noted, possibly from experimentation, that the difference in the falling times of two different weights was very small. In the early twelfth century, Ibn Bâjja, aka Avempace, may have made similar comments about the incorrectness of Aristotle's *Physics* and was certainly aware of the effects of air resistance upon falling bodies. During the sixteenth century, Francesco Beato, Luca Ghini, Domingo de Soto, Giovanni Bellaso, Girolamo Borro and Giuseppe Moletti are all recorded as having made analogous comments following falling-body experiments and/or published their ideas on the subject themselves.

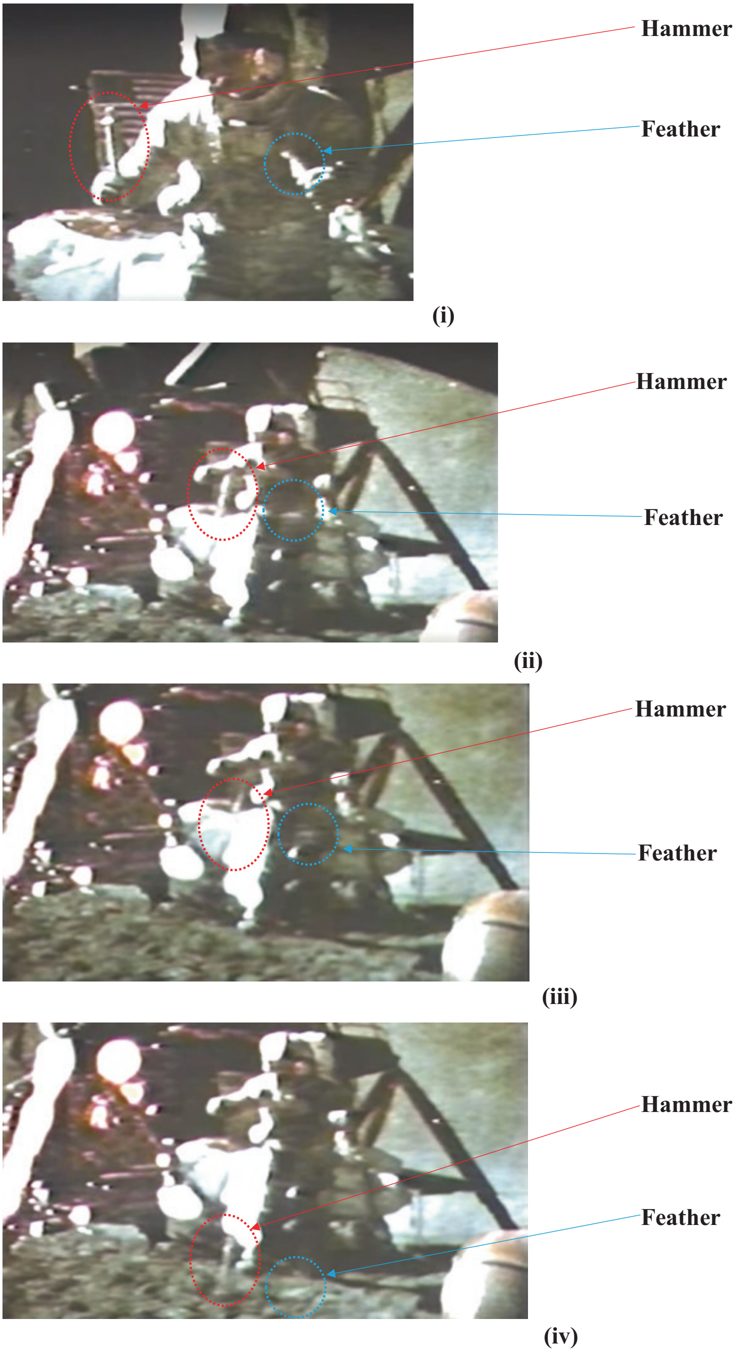

Figure 2.1 1971: Apollo 15—Astronaut David Scott showing that a geological hammer and a falcon's feather do fall at the same rate when in the vacuum of the Moon's surface. (Reproduced by courtesy of NASA—the original video, from which these images are frame-grabs, may be found at https://solarsystem.nasa.gov/resources/329/the-apollo-15-hammer-feather-drop/)

Galileo

The first clearly described and published experimental investigations of gravity, of which we now have records, began with Simon Stevin, or Stevinus. Stevin, in 1586, published a note in Flemish about dropping lead balls from a church tower in Delft. He found that when two balls of lead, one ten times the weight of the other, were released simultaneously to fall a distance of about 30 feet, or 10 m, the noises of their impacts with the ground also occurred simultaneously. From this he concluded that objects of different weights fell at the same rate and thus, to the consternation of most of his contemporaries, contradicted Aristotle's assertion. Stevin's work, however, did not become widely known, and so it is Galileo Galilei's (Figure 2.2) related investigations a few years later which have gained most of the credit for the initial quantifying of the properties of gravity.

Figure 2.2 Statue of Galileo Galilei in the Uffizi gallery, Florence. (Public domain. Reproduced by courtesy of Pixabay, image by wgbieber)