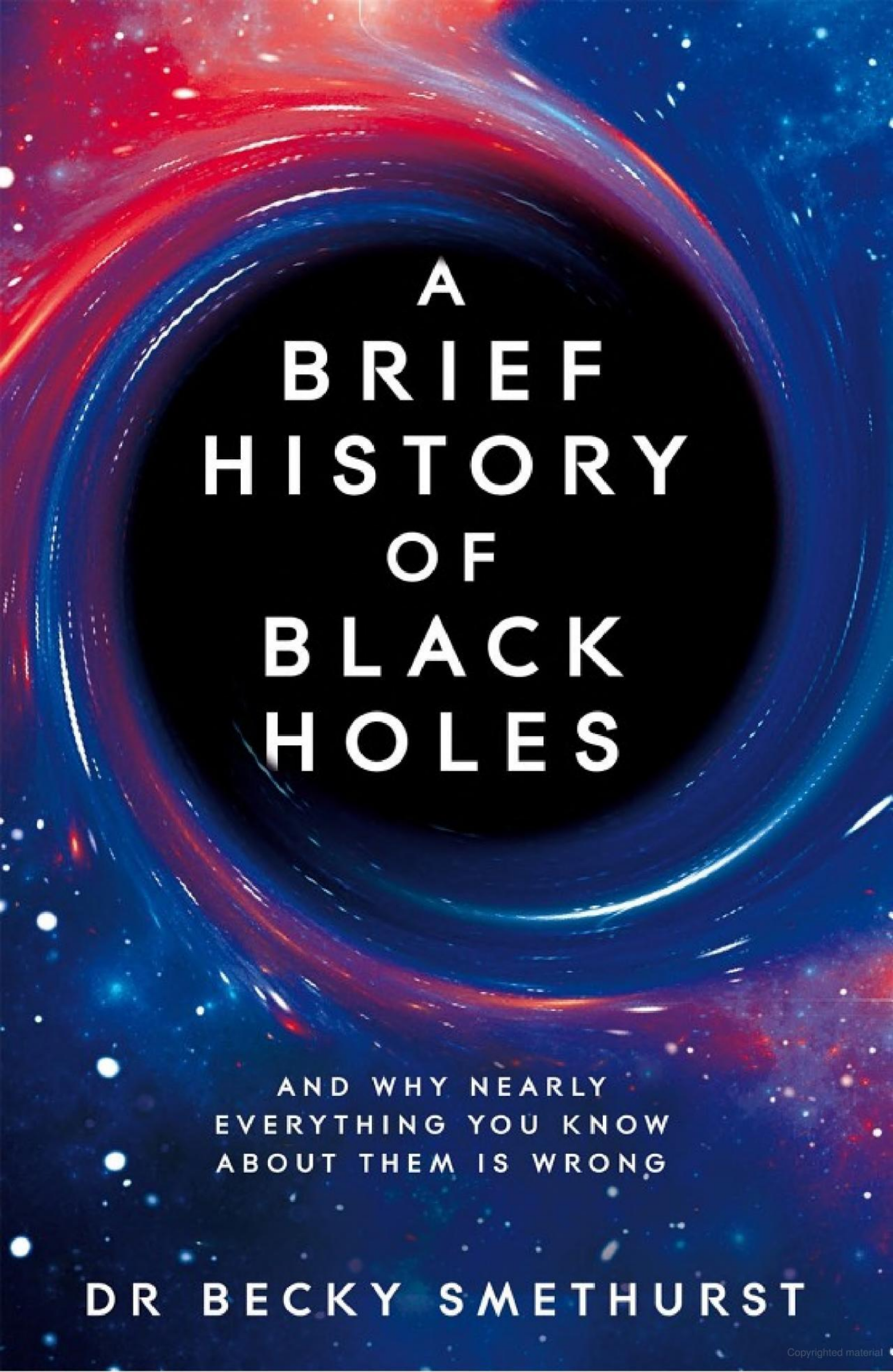
A BRIEF HISTORY OF BLACK HOLES
AND WHY NEARLY EVERYTHING YOU KNOW ABOUT THEM IS WRONG
DR BECKY SMETHURST

Contents

PROLOGUE

Standing on the shoulders of giants

At this very moment, as you sit down and relax to read this book, you are moving at an incredible speed. Earth is currently spinning on its axis, moving us through the relentless march of time from one day to the next. Simultaneously, it is orbiting around the Sun, moving us through the changing of the seasons.

But that's not all. The Sun is just one star in the Milky Way, our galaxy of over 100 billion stars. The Sun is not unique and it is not at the centre. In fact, it's fairly average and unremarkable as stars go. The Solar System is contained in a minor (seeing a pattern here?) spiral arm of the Milky Way known as the Orion Arm, and the Milky Way itself is also a fairly generic spiral-shaped island of stars – not too big, not too small.

So, this means that along with the speed of the Earth spinning, and the speed of the Earth orbiting the Sun, we are also moving around the centre of the Milky Way at a speed of 450,000 miles per hour. And what do we find at that centre? A supermassive black hole.

Yes – right now, you are orbiting a black hole. A place in space with so much material squashed in, that is so dense, that not even light – travelling at the fastest speed there is – has enough energy to win in a tug-of-war against a black hole's gravity, once it gets too close. The idea of black holes has both captivated and frustrated physicists for decades. Mathematically, we describe them as an infinitely dense, infinitesimally small point, surrounded by an unknowing sphere from which we get no light and no information. No information means no data, no data means no experiments, and no experiments means no knowledge of what lies 'inside' a black hole.

As a scientist, the aim is always to see the bigger picture. As we zoom out of our backyard of the Solar System to encompass the whole of the Milky Way, and then even further afield to see the billions of other galaxies across the entire Universe, we find that black holes are always in the gravitational driving seat. The black hole at the centre of the Milky Way, the one currently responsible for your motion through space, is about 4 million times heavier than our Sun; which is why it's dubbed a *supermassive* black hole. While that may sound big, I've seen bigger. Once again, the Milky Way's black hole is fairly average, relatively speaking. It's not that massive, that energetic, or that active either, making it nearly impossible to spot.[1]

The fact that I can accept those statements as a given, practically taking them for granted every single day, is remarkable. It was only at the end of the twentieth century that we finally realised that at the centre of every galaxy there was a supermassive black hole; a reminder that while astronomy is one of the oldest practices, carried out by ancient civilisations the world over, astrophysics – actually explaining the physics behind what astronomers see – is still a relatively new science. The advancements in technology throughout the twentieth and twenty-first centuries have only just begun to scratch the surface of the mysteries of the Universe.

Recently, I got wonderfully lost in a sprawling second-hand bookshop[2] and came across a book called *Modern Astronomy* written in 1901. In the introduction, the author, Herbert Hall Turner, states:

> *Before 1875 (the date must not be regarded too precisely), there was a vague feeling that the methods of astronomical work had reached something like a finality: since that time there is scarcely one of them that has not been considerably altered.*

Herbert was referring to the invention of the photographic plate. Scientists were no longer sketching what they saw through telescopes but recording exactly what was seen onto huge metal plates coated in a chemical that reacted to light. In addition, telescopes were getting larger, meaning they could collect more light to see fainter and smaller things. On page forty-five of my copy, there's a wonderful diagram showing how telescope diameters had increased from a measly ten inches in the 1830s to a whopping forty inches by the end of the nineteenth century. At the time of writing, the largest telescope currently under construction is the Thirty Metre Telescope in Hawai'i, which has a mirror to collect light which is, you guessed it, thirty metres across – about 1,181 inches in Herbert's money, so we've come a long way since the 1890s.

What I love about Herbert Hall Turner's book (and the reason I just *had* to buy it) is that it serves as a reminder of how quickly perspectives can shift in science. There is nothing in the book that I or my colleagues doing astronomy research today would recognise as 'modern', and I can imagine that in 120 years a future astronomer reading this book would probably think the same. For example, in 1901 the size of the entire Universe was thought to stretch to only the most distance stars at the edge of the Milky Way – about 100,000 light years away. We did not know there were other islands of billions of stars, other galaxies, out there in the vastness of the expanding Universe.

On page 228 of *Modern Astronomy*, there's an image taken with a photographic plate of what's labelled the 'Andromeda nebula'. It is instantly recognisable as the Andromeda *galaxy* (or perhaps to most people as a former Apple Mac desktop background image). Andromeda is one of the nearest galactic neighbours to the Milky Way, an island in the Universe containing of over 1 trillion stars. The image looks nearly identical to one an amateur astronomer might take from their back garden today. But even with the advancement of photographic plate technology at the end of the nineteenth century, which enabled the first images of Andromeda to be recorded, there wasn't an immediate leap to understanding what it actually was. At the time, it was still dubbed a 'nebula' – a fuzzy, dusty, not-star-like thing that was thought to be somewhere in the Milky Way, the same distance away as most stars. It took until the 1920s for its true nature as an island of stars in its own right, millions of light years away from the Milky Way, to be known. This discovery fundamentally shifted our entire perspective on our position in, and the scale of, the Universe. Overnight, our world view changed as the Universe's true size was appreciated for the first time. Humans were an even tinier drop in an even larger ocean than we had ever realised before.

The fact that we've only really appreciated the true scale of the Universe for the past 100 years or so is, in my opinion, the best example of how young of a science astrophysics truly is. The pace of advancement in the twentieth century has far exceeded even the wildest dreams of Herbert Hall Turner in 1901. In 1901, the idea of a black hole had barely crossed anyone's mind. By the 1920s, black holes were merely theoretical curiosities, ones that were particularly infuriating to physicists like Albert Einstein because they broke equations and seemed unnatural. By the 1960s, black holes had been accepted, theoretically at least, thanks in part to the work of British physicists Stephen Hawking and Roger Penrose and New Zealand mathematician Roy Kerr, who solved Einstein's general relativity equations for a spinning black hole. This led, in the early 1970s, to the first tentative proposal that at the centre of the Milky Way was a black hole. Let's just put that into context for a minute. Humans managed to put someone on the Moon before we could even comprehend that all our lives have been spent inexorably orbiting around a black hole.

It was only in 2002 that observations confirmed that the only thing that could possibly be in the centre of the Milky Way was a supermassive black hole. As someone who has been doing research on black holes for less than ten years, I often need reminding of that fact. I think everyone has a tendency to forget the things that, even up until recently, we didn't know. Whether that's what life was like before smartphones, or that we have only been able to map the entire human genome this millennium. It's understanding the history of science that allows us to better appreciate the knowledge we now hold dear. A look back into science history is like riding the collective train of thought of thousands of researchers. It puts into perspective those theories that we are so used to parroting we forget the fire in which they were first forged. The evolution of an idea helps us to understand why certain ideas were discarded and some were championed.[3]

It's a thought I have a lot when people challenge the existence of dark matter. Dark matter is matter that we know is there because of its gravitational pull, but we cannot see it because it does not interact with light. People question how plausible it really is that we're unable to see what we think makes up 85 per cent of all the matter in the Universe. Surely there must be some other thing we've not yet thought of? Now, I would never be so arrogant as to claim that we have indeed thought of absolutely everything, because the Universe is constantly keeping us on our toes. But what people forget is that the idea of dark matter didn't just pop up fully formed one day to explain away some curiosity about the Universe. It came about after over three decades worth of observations and research pointed to no other plausible conclusion. In fact, scientists dragged their feet for years, refusing to believe that dark matter was the answer; but in the end the evidence was just overwhelming. Most observationally confirmed scientific theories are shouted about from the rooftops; dark matter, however, must have been the most begrudgingly agreed upon theory in all of human history. It forced people to admit we knew far less than we thought we did, a humbling experience for anybody.

That's what science is all about: admitting the things we don't know. Once we do that, we can make progress, whether for science, for knowledge, or for society in its entirety. Humanity as a whole progresses thanks to advancements in knowledge and in technology, with the two driving each other. A thirst for more knowledge about the size and contents of the Universe, to see further and fainter things, drove the advancement of telescopes (from forty inches across in 1901 to thirty metres across in 2021). Tired of cumbersome photographic plates, the invention of digital light detectors was pioneered by astronomers, and now we all carry a digital camera around in our pockets. That invention saw improvements to image analysis techniques, which were needed to understand the more detailed digital observations. Those techniques then fed into medical imaging, such as MRIs and CT scanners, now used to diagnose a whole host of ailments. Getting a scan of the inside of your body would have been unimaginable a mere century ago.

So, like all scientists, my research on the effects of black holes stands on the shoulders of the giants who have come before me: the likes of Albert Einstein, Stephen Hawking, Sir Roger Penrose, Subrahmanyan Chandrasekhar, Dame Jocelyn Bell Burnell, Sir Martin Rees, Roy Kerr and Andrea Ghez to name but a few. I can build upon the answers that they worked so hard and so long for, to pose new questions of my own.

It has taken over 500 years of scientific endeavours to just scratch the surface of what black holes are. It's only by delving into that history that we can hope to understand this strange and enigmatic phenomena of our Universe, one we still know so little about. From the discovery of the smallest, to the largest; the possibility of the first black hole, to the last; and why they're even called black holes in the first place. Our jaunt through science history will take us on a journey from the centre of the Milky Way to the edges of the visible Universe, and even consider the question that has intrigued people for decades: what would we see if we 'fell' into a black hole?

To me, it's incredible that science can even hope to answer questions like that, while simultaneously surprising us with something new. Because, while black holes have long been thought to be the dark hearts of galaxies, it turns out they're not 'black' at all. Over the years, science has taught us that black holes are in fact the brightest objects in the entire Universe.

1

Why the stars shine

The next time you have a clear night, with no clouds spoiling the view, stand with your eyes closed for a few minutes by the door to outside. Before you step out and look up, give your eyes time to adjust to the darkness. Even young children notice how when you first turn the bedside light off before sleep, the room plunges into pitch blackness. But wake in the middle of the night and you can see shapes and features again in even the lowest of lights.

So if you want to truly be awed by the night sky, let your eyes take a break from the bright lights of home first. Let your night vision develop and you won't be disappointed. Only once your eyes are primed and ready can you then step outside and change your perspective on the world. Instead of looking down, or out, look *up* and watch thousands of stars burst into view. The longer you stand in the darkness, the better your night vision will be and the more stars will pepper the sky with tiny pinpricks of light.

As you gaze skyward, you might spot things you recognise, such as shapes in the patterns of stars that we call constellations, like Orion or the Plough.[4] Then there'll be things that aren't familiar. But by just gazing at the sky and noting the brightness or perhaps the position of a star, you join an incredibly long list of humans from civilisations the world over, both ancient and new, that have done the very same and found themselves awed by the beauty of the sky. The stars and planets have long held an important cultural, religious or practical role in society. From navigation by land or sea, to helping people keep track of the seasons, leading to the development of the first calendars.

In the modern world, we have lost that innate connection with the night sky, with many of us not able to notice how the stars change with the seasons or pick out visiting comets because of the ever-present light pollution in cities drowning them all out. If you're lucky enough to live somewhere you can see the stars, perhaps you might notice how the position of the Moon changes from night to night, or that one particularly bright 'star' wanders across the sky as the months go by. The Greeks also noticed these 'wandering stars' and dubbed them just that:

planētai, meaning wanderer (the root of the modern English word, planet).

But not all of us can just look up and enjoy the view for what it is. Some of us want answers; an explanation of the things we see in the sky. It's natural human curiosity. The very nature of what stars are and how they shine were questions that plagued humanity for centuries. In 1584, Italian philosopher Giordano Bruno was the first to suggest that the stars themselves might be distant Suns, even going so far as to suggest that they may also have planets of their own orbiting them. This was an idea that was incredibly controversial at the time, and came just forty-one years after the neat mathematical idea of the Sun, and not the Earth, being the centre of the Solar System was published by Polish mathematician and philosopher Nicholas Copernicus. Copernicus was a big fan of the simplicity and mathematical beauty of circles, and thought that if you arranged the Solar System with the Sun at the centre and the planets moving around it on circular paths, that would be the most mathematically beautiful way of arranging things. He wasn't serious about it astronomically, necessarily, he just enjoyed the geometry of the whole idea.

But after a few more decades, there were those that started to support the idea astronomically, like Bruno and his fellow Italian astronomer Galileo Galilei, who would both eventually be punished for this supposed heresy against Catholic doctrine. It would take the combined efforts of Tycho Brahe, Johannes Kepler and Isaac Newton over the next century or so to compile overwhelming evidence in favour of the Sun being at the centre of the Solar System, and for the idea to finally be accepted both scientifically and publicly following the publication of Newton's *Principia* in 1687. First, Newton determined the laws of gravity and the movements of the planets in their orbits. The same force that keeps us trapped here on the Earth's surface is what causes the Moon to orbit the Earth and the Earth to orbit the Sun. These roughly circular orbits of planets around the Sun explained why the planets appeared to move backwards night after night in the sky for parts of the year, a phenomenon known as retrograde motion. Those planets closer to the Sun appear to be moving

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