In Search of Dark Matter

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Authors' preface

Although science teachers often tell their students that the periodic table of the elements shows what the Universe is made of, this is not true. We now know that most of the Universe – about 96% of it – is made of dark material that defies brief description, and certainly is not represented by Mendeleev's periodic table. This unseen 'dark matter' is the subject of this book. While it is true that the nature of this dark matter is largely irrelevant in day-to-day living, it really should be included in the main-stream science curricula. Science is supposed to be about truth and the nature of the Universe, and yet we still teach our children that the Universe is made up of a hundred or so elements and nothing more.

Dark matter provides a further reminder that we humans are not essential to the Universe. Ever since Copernicus and others suggested that the Earth was not the centre of the Universe, humans have been on a slide away from cosmic significance. At first we were not at the centre of the Solar System, and then the Sun became just another star in the Milky Way, not even in the centre of our host Galaxy. By this stage the Earth and its inhabitants had vanished like a speck of dust in a storm. This was a shock. In the 1930s Edwin Hubble showed that the Milky Way, vast as it is, is a mere 'island Universe' far removed from anywhere special; and even our home galaxy was suddenly insignificant in a sea of galaxies, then clusters of galaxies. Now astronomers have revealed that we are not even made of the same stuff as most of the Universe. While our planet – our bodies, even – are tangible and visible, most of the matter in the Universe is not. Our Universe is made of darkness. How do we respond to that?

The last fifty years have seen an extraordinary change in how we view the Universe. The discoveries that perpetuated the Copernican revolution into the twentieth century have led to ever more fundamental discoveries about how the Universe is put together. But parallel to the discovery of the nature of our Galaxy and galaxies in general ran a story almost as hidden as its subject. The laws of gravity that Newton and later Einstein propounded were put to good use in discovering new worlds in our Solar System, namely Neptune and Pluto. These same techniques – of looking for the gravitational effects on visible objects by unseen objects – led astronomers to realise that there exists much more matter than we can see. This book tells that story. It is a story of false trails that ultimately pointed in the right direction; of scientists' arrogance and humility, curiosity and puzzlement. But most of all it is a story that shows the persistent nature of science and scientists who consistently reveal just how much more there is to learn.

The problem is that each new discovery seems to show not more about the Universe, but simply how much we have yet to learn. It is like a person who wakes in a dark cave with only a candle to push back the darkness. The feeble glow reveals little but the floor of the cave and the surrounding darkness. Hope rises when a torch is found; but the additional luminance does not reveal the walls of the cave, rather the extent of the darkness. Just how far does the darkness extend? We have yet to find out. This book describes how far into the night we can currently see.

This is also a story about science and scientists. All but one of the contributors is a scientist with expertise in specific aspects of the dark matter problem. The non-scientist of the group is Geoff McNamara, a teacher and writer, who was responsible for bringing the story together from the various contributors. Most of the historical and contemporary astronomical research into the location and quantity of dark matter was related by Ken Freeman, who has a long career in dark matter research since its revival in the late 1960s. Professor Warrick Couch, Head of the School of Physics at the University of New South Wales, relates how gravitational lensing has evolved into a technique that is now used to help map out the location and amount of dark matter in galaxies and galaxy clusters. The story of the exotic particles that perhaps make up dark matter is told in Chapters 11, 12 and 13. These chapters rely heavily on technical input from Professor Ray Volkas of the School of Physics, University of Melbourne, and his advice on particle astrophysics is gratefully acknowledged. Finally, Dr Charley Lineweaver of the Research School of Astronomy & Astrophysics, Australian National University, relates the implications of dark matter and the relative newcomer – dark energy – for the long-term fate of the Universe.

How do students react when their insignificance in time, space and now matter is revealed to them? As the immensity of the Universe is revealed, as the unimaginable distances in time and space become apparent and they realise they are not even made of the same stuff as the rest of the Universe, they feel small and insignificant. But this phase soon passes, and curiosity takes over. Students with very different academic ability and understanding of things astronomical all come to the same point: they want to know more. These young people are all scientists at heart – even if only a few will have the opportunity to pursue the subject professionally. It is for our students and like-minded readers everywhere that this book has been written.

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List of illustrations

Prologue

The quest for darkness

Astronomy was once a quest for light. For millions of years, humans stared wide-eyed at the night sky, trying to piece together the nature of the Universe in which we live. But because of the limitations of the naked eye, the vast majority of our ancestors never suspected, and none knew, that the stars were other suns and the planets other worlds. Such revelations had to wait until the invention of the telescope – an instrument that simultaneously created and fulfilled the possibility of seeing fainter and more distant objects in the Universe. While the earliest telescopes were capable of little more than today's toy telescopes, they nonetheless revealed for the first time the moons of Jupiter, craters on our own Moon, and the myriad of fainter stars in the Milky Way. As telescopic power grew it was assumed that telescopes, being light-gatherers, would reveal ever more of the Universe that surrounds us, and that they would eventually reveal everything. Indeed, modern telescopes have provided us with images of objects so distant that they are not only close to the edge of the Universe, but almost at the edge of physical detectability. The interpretation of what telescopes reveal aside, without their light-gathering capability our understanding of the Universe might never have progressed beyond the Milky Way.

Our story begins in the first few decades of the twentieth century, when the first truly modern telescopes were built atop high mountains. Sitting in their new, ivory-coloured towers, astronomers were literally and metaphorically closer to the stars than they had ever been before. These were heady times for astronomers: our parochial view of the Universe in which the Milky Way was the dominant feature expanded to one where our Galaxy played a minor role. Stars gathered into galaxies; galaxies into clusters of galaxies. The general expansion of the Universe was independently and simultaneously discovered and explained, and astronomy and physics forged a partnership that is now inseparable: astronomers turned to physics for explanations of what they saw, and physicists realised the Universe was a laboratory of immense size and energies.

Despite the philosophical ramifications of these discoveries, or perhaps because of them, the future of astronomy looked bright. To astronomers, the night was ablaze with the light of uncountable suns at almost immeasurable distances. But everywhere astronomers looked, something was missing. The stars and galaxies sparkled in the night as far as the eye could see, like moonlight off an ocean, but their behaviour was peculiar: rather than huddling together in the cold emptiness of space bound by their own gravity alone, the stars and galaxies seemed to be pulled this way and that by dark, unexplained currents that seemed to permeate the cosmos. Far from dominating the Universe, the stars and galaxies behaved as if they were mere flotsam on a cosmic sea.

The problem is as simple to understand as it has been difficult to solve. There is only one way to interpret gravity, and that is the existence of matter. Everything in the Universe has a gravitational pull on everything else – a phenomenon that holds solar systems, star clusters, and galaxies together. The dynamics of the stars and galaxies hinted at more matter than meets the eye. But when astronomers tried to find the source of the gravity they found… nothing. As larger telescopes penetrated deeper into space they revealed structures on increasingly larger scales, yet every turn of the telescope revealed more of the same unexplained gravitational influence. Not only that, but the larger the scale – from stars to galaxies to clusters of galaxies – the greater the mysterious effect seemed to be. The further astronomers looked, the less of the Universe they saw.

Because of its invisibility, the unseen matter was once called 'missing mass'; but this is not a good term, since the location is well known, and astronomers can literally point their telescopes to it. Yet to even the largest, most powerful telescopes it remains invisible against the blackness of space, and so it has become known as 'dark matter'. However, this term understates the significance of the concept it represents. The dark matter mystery has evolved from simply another unsolved astronomical problem to one of the most important cosmological questions of all time. One reason is that despite the fact that it seems to outweigh visible matter by as much as a hundred times, no-one knows what dark matter is made of. Is this simply a limitation of the way we observe the Universe? Perhaps. But keep in mind that when dark matter was originally detected astronomers were limited to using optical telescopes; that is, they saw the Universe only in visible light. In the intervening seventy years or so, the Universe has been studied in a myriad of new wavelengths, each revealing new forms of previously invisible matter, including interstellar gas and dust, neutron stars, radio galaxies and black holes. But the addition of these previously unseen sources of matter falls a long way short of accounting for the effects of dark matter.

It could turn out that all this time we have simply been looking for the wrong kind of matter. The very term 'dark matter' implies matter that is non-luminous, simply not giving off any light. What if it is not even made of baryonic matter – the familiar protons and neutrons that make up stars and planets? (See Appendix 1.) Perhaps we should be looking for non-baryonic matter – exotic particles, many of which have yet to be discovered. Perhaps most of the Universe is not made of the same stuff as we are. Such a revolution in our thinking would not be unprecedented. Four hundred years ago the so-called Copernican Revolution displaced the Earth from the centre of the Universe. As has been noted by David

Schramm, we could now be experiencing the ultimate Copernican Revolution, in that not only are we not at the centre of the Universe, we may not even be made of the same stuff as most of the Universe.

There are many candidates lining up for the role of dark matter: neutron stars, primordial black holes, dead stars, neutrinos, and a whole family of exotic particles called WIMPs. We shall take a look at each of these and other candidates in turn, and see how scientists are trying to find them. However, we need to be careful about what conclusions we draw about the nature of dark matter. Astronomers are very creative storytellers, and can always construct an hypothesis to fit the facts; and the fewer facts available, the easier it is to fit the hypothesis. As astronomers grope in the darkness towards a fuller understanding of an astronomical problem it is important to invoke a principle known as Occam's Razor: the simplest – and usually most elegant – explanation is the one that is to be preferred. In the case of dark matter, this means it is better to assume that there is one sort of dark matter to account for the gravitational effects seen at Galactic and extragalactic scales. However, as our story unfolds you will see that it is more likely that things are not as simple as that. In fact, we might have to learn to live with several different sorts of dark matter, each providing the gravitational influence we see on different scales. Whatever it is made of, dark matter certainly played a role in the origin of the Universe. Without it, the Universe would have no galaxies, no stars, and possibly no-one to wonder why. Yet it does have them, and here we are.

Just as dark matter played a crucial role in the origin of the Universe, it may be a major factor in the cosmological tug-of-war between the expansion of the Universe and its self-gravitation. The expansion of the Universe – the implication of which was the Big Bang, the primordial fireball which gave birth to the Universe – was revealed around the same time as the discovery of dark matter. This expansion is struggling against the gravitational pull of the matter it contains. If the Universe contains too little mass, it will expand forever; too much and it will one day collapse in on itself again. Between these two extremes is perfect balance between gravity and expansion – a 'critical density' that is just sufficient to stop the Universe expanding at some infinitely distant time. All the visible matter in the Universe adds up to only a tiny fraction of the critical density. Can dark matter tip the scales? Or is the Universe dominated by something even more bizarre, such as the energy that is created by the vacuum of space that is forcing the Universe to expand forever against even the mighty pull of dark matter? If true, then the bulk of the Universe is truly dark.

It is ironic that as telescopes became larger, and their detectors more sensitive and wide ranging in their spectral reach, they revealed not a Universe filled with light, but one plunged into darkness; not a Universe dominated by blazing suns and galaxies, but one ruled by an invisible, as yet unidentified, substance. The stars and galaxies may sparkle like jewels, but in a sense that is only because they shine against the velvet blackness of dark matter. Despite their telescopes, their detectors, and their initial objections, astronomers have been forced to ponder a largely invisible Universe. Yet they continue to investigate dark matter through their telescopes, in their laboratories and with their theories. It is an intense search that is taxing some of the most brilliant minds the world has ever known, and occupies great slices of precious observing time on the world's most advanced telescopes. It seems strange to use telescopes to search for something invisible, something that emits no light. But just as such investigations revealed the outer members of our Solar System, so the search for dark matter will eventually reveal the rest of the Universe. It may have begun as a quest for light, but now astronomy is a quest for darkness.

1

How to weigh galaxies

> There are no purely observational facts about the heavenly bodies. Astronomical measurements are, without exception, measurements of phenomena occurring in a terrestrial observatory or station; it is by theory that they are translated into knowledge of a Universe outside.
>
> Arthur S. Eddington, *The Expanding Universe*, 1933

INTRODUCTION

The Universe seems to be dominated by dark matter. By studying the dynamics of visible matter – the movements of stars and galaxies – astronomers* have not only found that there are forms of matter other than that we can see, but that this luminous matter is actually in the minority, outweighed in some cases a hundred to one by dark matter. To say that it 'seems' to be dominated is scientific caution, as nothing is ever really proven in science. Nonetheless the evidence for dark matter is overwhelming. Using sophisticated techniques, astronomers are now able to study the kaleidoscopic phenomena of the Universe with increasing precision, and ever tinier movements of ever fainter objects are becoming observable. Time is routinely measured on scales from minutely split seconds to the very age of the Universe. The visible Universe has now been studied using almost the entire spectrum of electromagnetism, and at every turn, evidence for dark matter is revealed.

What is it, specifically, that suggests to us that dark matter exists at all, let alone in such vast quantities? The answer lies in the conflict between two measurements of the mass of the Universe: luminous mass and gravitational mass. In other words, there is a conflict between the total mass of all we see in the form of luminous stars and galaxies, and the mass implied by their motion through space which in turn implies a gravitating, although unseen, mass. These two concepts – luminous mass and gravitating mass – are central to the story of

* Throughout this book we will refer to astronomers who study dark matter, although those that study the problem now include physicists, astrophysicists and engineers. The subject is so interwoven within these fields that it is now impossible to distinguish them.

dark matter, and so we begin by talking about how astronomers weigh the Universe. (Moreover, a new spectrum, that of gravitational waves – ripples in the fabric of spacetime – may soon be opened for study.)

HOW TO WEIGH GALAXIES

The basic tool astronomers use to determine the mass of a system of stars or galaxies is to study their motion through space, and then compare that motion with the gravitational force needed to keep the system bound together. It was Newton who first showed that the motion of objects could be explained by the sum of various types of forces. When different forces act, the resultant motion is the sum of the effect of each different force. Especially in the case of gravity, we have a law which epitomises the concept of laws in physics: Newton's laws apply equally everywhere in the Universe. The balance between motion and gravity is often obvious and beautiful, perhaps best visualised by thinking in Newtonian terms of a balance of forces. We are surrounded by some wonderful examples, such as the Moon which silently orbits the Earth with mathematical precision simply because the gravitational attraction between the two bodies almost exactly balances the Moon's desire to keep moving in a straight line. Some examples are stunning; for example, the rings of Saturn, which are made up of countless particles. The rings display a symmetry so perfect that it is tempting to ask why the particles do not fly around the planet like a halo of moths around a streetlamp. Indeed, why do they not simply fly off into space, or plummet towards the planet? The solution is that many of the original particles that must have surrounded Saturn *did* fly off into space or become part of the planet, but they did it long ago. What we see today is all that remains – those particles that are trapped in a delicate balance between the forces of motion and gravitation. This same balance is repeated in the congregation of asteroids into the asteroid belt, or the spiral formation of stars and gas within the Milky Way.

NEWTONIAN GRAVITATION AND FINDING THE INVISIBLE

While it has been said that Newton's ideas on gravitation are simply an approximation, it is wrong to underestimate them. They have been good enough to reveal unseen masses at a variety of scales. In fact, the first ever experience with dark matter occurred in our own backyard, the outer Solar System. Despite its success at describing the motions of most of the known planets, for a while it seemed Newton's laws were failing with the seventh planet, Uranus, whose erratic wanderings refused to follow Newton's laws of gravity. No matter how many ways the celestial mechanicians manipulated the numbers, Uranus just would not follow its predicted path among the stars. Here was a problem. Could it be that Newton's gravitation had a limited range, and that beyond a certain distance from the Sun it broke down, allowing planets to wander unleashed