
SHADOWLANDS
Quest for Mirror Matter
in the Universe

The picture on the cover shows the crab nebula – the remnants of a star which exploded in 1054. This photograph was taken at the European Southern Observatory. (Credit: FORS Team, 8.2-metre VLT ESO).

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Preface

My purpose in writing this book is two-fold. First, many non-specialists ask me to explain the mirror matter idea and the scientific evidence for it. Second, science is so specialized these days that many people who know a lot about one field often know little about another. Mirror matter, if it exists, would lead to rather important implications for several scientific fields, including: particle physics, astrophysics, cosmology, meteoritics and planetary science. Thus, it seemed to me that an interesting challenge would be to write a book explaining the motivation for mirror matter and its evidence which could usefully serve these two communities (that is, both specialists and non-specialists alike). Such a venture, though, is not without risks of various kinds. Let me state at the outset that the mirror matter idea is not established fact; it is an example of cutting-edge science in progress. It is my hope that people who read this book will be infected by, or at least understand, my enthusiasm for this subject, and why I think it is one of the most interesting questions in science at the moment.

The process of writing this book gave me the opportunity to re-think many of the original arguments. Some 'gaps' in my knowledge were filled in, and a few new directions explored. Some material is therefore completely new, although most of it has appeared in the technical scientific literature previously. I have only cited this scientific literature sparingly, but nevertheless I have endeavoured to properly credit the people responsible for the main original ideas.

It seems only yesterday that I learned as a student that mirror reflection symmetry was not respected by the fundamental interactions of nature. Electrons and other elementary particles are, in a sense, 'left-handed'. Although most scientists have simply come to accept that God is 'left-handed', somehow it always bothered me....

One sunny afternoon in May 1991 a rather remarkable thought occurred to me. While playing with an unrelated idea, it suddenly struck me that there was a subtle yet simple way in which mirror reflection symmetry could still exist. Nature's mirror could be unbroken if each type of ordinary particle has a shadowy mirror partner. The left-handedness of the ordinary particles could then be balanced by the right-handedness of the mirror particles. So there you have it, mirror reflection symmetry can exist but requires something profoundly new. It requires the existence of a completely new form of matter called 'mirror matter'.

At first, it seemed too fantastic to really exist. Yet, over the last few years it appears that almost *every* astrophysical and experimental prediction of the mirror matter theory has actually been observed by observations and experiments: There is fascinating evidence for mirror matter in the Universe from astronomical observations suggesting that most of our galaxy is composed of exotic dark material called 'dark matter'. Recent particle physics experiments have revealed unexpected properties of ghostly particles called 'neutrinos' and weird matter anti-matter atoms. This unexpected behaviour is expected if mirror matter exists. Most remarkable of all is the evidence that our planet is frequently bombarded by mirror matter asteroid or comet sized objects, causing puzzling events such as the huge 1908 Siberian explosion which felled more than two thousand square kilometres of native forests without leaving a single meteorite fragment behind! Altogether I will discuss seven major puzzles in astrophysics and particle physics each arguing in favour of the mirror matter hypothesis. There are indeed seven wonders of the mirror world...

New data from current and future experiments will keep coming in even as this book is being printed. Unfortunately, I am not a fortune teller and do not know what these future experiments and observations will find. However, I can predict what they will find if mirror reflection symmetry and hence mirror matter exists. The case for mirror matter will therefore either strengthen or weaken as new data comes in and future experiments are done. In the meantime, I advise you to sit back, relax and let me take you on a journey exploring one of the boldest scientific ideas ever proposed.

No scientist works in isolation and I am no exception. I have had fruitful collaborations on mirror matter with a number of very creative people, including Sergei Gninenko, Sasha Ignatiev, Henry Lew, Zurab Silagadze, Ray Volkas and T. L. Yoon. I have enjoyed interesting correspondence on some aspects of this subject with Sergei Blinnikov, Zdenek Cepelcha and Andrei Ol'khovatov. In addition, I would like to acknowledge invaluable support over the years from many friends and colleagues including in particular, Pasquale Di Bari, John Eastman, Greg Filewood, Dave Howland, Girish Joshi, Matthew Tully, and Nick Whitelegg. I am also grateful to many of the above people, and also Jaci Anderson and Glen Deen for providing me with useful comments on the manuscript and Tony Nguyen for helping with the cover.

Of course, I thank my family most of all. It is to them that I dedicate this book.

Robert Foot
August 2001

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for Carolyn and James

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*There are more things in
Heaven and Earth, Horatio, than
are dreamt of in your philosophy.*

William Shakespeare – Hamlet.

PART I

Why Mirror Matter?

Chapter 1

Introduction

Shortly before his death in 1727, Isaac Newton reflected upon his life and wrote¹:

I don't know what I may appear to the world, but, as to myself I seem to have been only like a boy playing on the sea shore, and diverting myself in now and then finding a smoother pebble or a prettier shell than ordinary, whilst the great ocean of truth lay all undiscovered before me.

More recently in Stephen Hawking's *a brief history of time*, it is written²:

I still believe that there are grounds for cautious optimism that we may now be near the end of the search for the ultimate laws of nature.

The contrast between the current Lucasian Professor and the former holder of that position is striking. Hawking is not alone in his prophecy. It has been repeated with monotonous regularity since the days of Maxwell (1865). One day it may come true, but that day is a long way off. I believe that a revolution in science may be imminent. In fact, over the last decade, remarkable evidence from astronomy (studies of the very big) to studies of the elementary particles (the very small) suggest that a completely new type of matter exists – 'mirror matter'. The best ideas in science are usually very simple,

and fortunately mirror matter belongs to this category. I believe that the ideas and the evidence can be appreciated by anyone interested in science.

In the process of uncovering mirror matter we will encounter many recent and unexpected discoveries, including:

- Invisible stars which reveal their presence by gravitationally bending the light from more distant stars behind them. I will argue that these invisible stars are made of mirror matter which can simply explain why we don't see them.
- Planets orbiting nearby stars which are *eight times* closer to their star than the distance Mercury orbits the Sun. I will suggest that these unexpected planets are expected if they are made of mirror matter.
- Bizarre, apparently free-floating planets wandering through space. They can be more naturally interpreted as ordinary planets orbiting mirror stars, but I could be wrong!
- Strange and unexpected properties of elementary particles such as the ghostly neutrinos. These particles are emitted from the Sun and in other processes. However, half of them are missing! The missing neutrinos may have been transformed into mirror neutrinos as I will explain.
- I will also discuss a strange class of 'meteorite events' such as the huge Siberian 1908 explosion and other similar such explosions. There is evidence that these explosions are caused by the random collisions of our planet with orbiting 'mirror matter space-bodies'. Most remarkable of all is the real possibility that mirror matter remnants may still be in the ground today! Needless to say the possible uses of this new type of matter are not even imagined...

By the way, this is a (generally) serious scientific book. However, unlike other 'serious scientific books' this book does not claim to reveal the 'mind of God'. In fact, not many ridiculously grandiose statements will be made at all. Rather, it is simply a book about mirror reflection symmetry – and its far reaching implications.

Symmetry is a word frequently used in everyday language and we are all aware of what it means. Examples of symmetrical objects abound: flowers, butterflies, snowflakes, soccer balls and so on... In fact, as some of these examples illustrate, symmetry is often associated with beauty and vice versa. It is perhaps not surprising then that symmetry plays a pivotal role in our understanding of the elementary particles and their forces, but let me start at the beginning.

There are many distinct types of symmetry. The symmetry of a mushroom is completely different to the symmetry of a butterfly which in turn is completely different to the symmetry of a soccer ball. A butterfly is an example of the most familiar symmetry – ‘left-right’ symmetry. This symmetry occurs when two equal portions of a whole are the mirror image of each other. For obvious reasons, this symmetry is also called ‘mirror’ symmetry. A soccer ball is an example of another type of symmetry – rotational symmetry. In fact, it is an example of an object with three dimensional rotational symmetry because rotations around any axis do not change the appearance of the ball. Finally a straight fence or railway line are examples of objects which display another type of symmetry – translational symmetry. A railway line or fence looks the same as we move along it.

Fortunately the everyday usage of the concept of symmetry is exactly the same as its technical usage in science. Although it is often useful to describe symmetry in a mathematical way – this need not concern us. Here we need only discuss the ideas and concepts which is enough to glimpse the beautiful world of the elementary particles and their interactions.

Most people are aware that ordinary matter: you, me and everything else we see, except light itself, is composed of atoms. Although atoms are very tiny, approximately one ten millionth of a millimetre in size, they are still not the most fundamental building blocks of matter. Atoms are not *elementary* entities. Each individual Atom is made up of electrons and a compact nucleus, which in turn is made from protons and neutrons. There are about 100 different types of atoms depending on the number of electrons that they contain. The science of atoms, how they interact with each other to form molecules and how different molecules interact with each other is of

course the science of chemistry. However, we will not be involved so much with chemistry but with the most fundamental of the sciences – physics. One thing that physics is concerned with is the most basic questions that can be asked. For example, what are the properties of the elementary particles: protons, neutrons, electrons from which all matter is made? How do these particles interact with each other and with light?

One thing that has been learned over the years is that the interactions of elementary particles display a variety of symmetries. Some of these symmetries are quite familiar such as rotational symmetry and translational symmetry. Thus, the laws of physics remain the same whether we are in Melbourne or in Moscow, which means that Russian physics text books are useful in Australia and vice versa (after they are translated...). In addition to translations in space (and translations in language!) we can imagine translations in time. The laws of physics are the same today as yesterday or even a century ago, however our knowledge of these laws generally improves as time goes by. Hence, physics text books are not the same today as a century ago, yet the laws of physics are the same. There are still other more abstract symmetries of the elementary particle interactions. These are called ‘Lorentz symmetry’ and ‘gauge symmetry’, which are nevertheless quite elegant and natural once you get to know them.

Progress in science is rarely a smooth comfortable journey. Rapid progress generally occurs in brief intervals usually through new and unexpected experimental results and sometimes through novel theoretical ideas. Of course progress is most rapid when theory and experiment move together in harmony. One of the most remarkable theoretical ideas of the 20th century was the discovery of relativity theory in 1905 by Albert Einstein. Space and time were unified with time becoming the fourth dimension. Einstein suggested that the laws of physics were symmetrical under rotations in this four dimensional space-time, rather than just the three dimensions of space. The predictions of this theory, such as moving clocks must run more slowly, have been experimentally verified with tremendous precision. This is possible because Einstein’s theory not only tells us that moving clocks run more slowly, but it tells us exactly how

much more slowly! This four dimensional rotational symmetry of space-time is called ‘Lorentz symmetry’*.

There are four known fundamental forces in nature: gravity, electromagnetism, weak and strong nuclear forces. Gravity is quite familiar to most of us. It keeps our feet on the ground, it keeps our planet and all the other planets in our solar system in orbit around the Sun and it keeps the Sun in orbit around the centre of our galaxy. Electromagnetism is no less important – while it is gravity that holds us down, it is electromagnetism that stops us from falling through the floor. It is also the force responsible for electricity and magnetism. While the weak and strong nuclear forces are less familiar, they are nevertheless equally fundamental and important as the other more familiar forces. For example, the weak and strong nuclear force provides the energy which powers the Sun, without which our planet would be too cold to sustain life.

Today we know that three of these forces, electromagnetism, the weak and strong nuclear forces are, mathematically, very similar and fairly well understood. Gravity, on the other hand, is quite different and its relation to the other forces is somewhat mysterious. One reason is that gravity can be described in geometrical terms as a curvature of four dimensional space-time while the other three forces are described in terms of symmetries on an abstract ‘internal’ space, which is nothing to do with ordinary space-time that we know about. These peculiar symmetries of the electromagnetic, weak and strong nuclear forces are called ‘gauge symmetries’.

Evidently, symmetries are rather important in understanding the elementary particles and their forces. However, it is pertinent to recall that these symmetries were not always so obvious. I have already mentioned the case of Lorentz symmetry – the rather abstract idea that space and time can be treated mathematically as a four dimensional space-time. In fact, after the discovery of relativity theory and Lorentz symmetry, an English Physicist called Paul Dirac uncovered a big problem. In the late 1920’s Dirac noticed that a microscopic mathematical description of the electron consistent with

*In addition to Albert Einstein’s insight, important contributions to the relativity theory were made by others, including: Hendrik Lorentz, Hermann Minkowski and Henri Poincare.

Lorentz symmetry was not possible, unless something completely new existed. Nothing short of a new form of matter was required to reconcile Einstein's relativity theory with the quantum mechanical theory of the electron. This new form of matter, called 'anti-matter' was thereby theoretically predicted to exist.

Specifically, Dirac predicted that in addition to the particles that make up ordinary matter – the electrons, protons and neutrons, anti-particles called 'positrons' (or anti-electrons), 'anti-protons' and 'anti-neutrons' should all exist. The symmetry required each type of anti-particle to have the same mass as the corresponding particle. Positrons and anti-nuclei (made from anti-protons and anti-neutrons) should form 'anti-atoms'. However, anti-particles should annihilate when they meet ordinary particles producing gamma rays (high frequency light). History tells us that experiments shortly followed which dramatically confirmed the existence of Dirac's anti-particles. First, the discovery of the positron in 1932, and later, the discovery of anti-protons in the 1950's. Anti-matter is not science fantasy but science reality. Clearly, the idea of symmetry can have remarkable implications.

This book though, is concerned not with Lorentz symmetry but with left-right or mirror reflection symmetry. Let us now briefly look at the history of this symmetry. Before 1956 physicists had assumed that the laws of physics were symmetric under left-right symmetry. This would mean that for every fundamental microscopic process that is known to occur, the mirror image process should also occur. In fact left-right symmetry is such a familiar and plausible symmetry of nature that it was never seriously questioned until various experimental puzzles began appearing in the 1950's. These puzzles led T. D. Lee and C. N. Yang to suggest that the weak nuclear force does not display left-right symmetry. They proposed an experiment to directly test the idea involving the β -decay of an unstable isotope...

At the time, most scientists didn't expect that mirror symmetry could really be broken. The prevailing scepticism was summed up by Wolfgang Pauli when he wrote in December 1956³:

I am however prepared to bet that the experiment will be decided in favour of mirror invariance. For in spite of Yang and Lee, I don't believe that God is a weak left-hander.

However, Pauli was not so foolish as to let his beliefs get in the way of science. He did agree that experiments should be done to check it⁴:

I believe in reflection invariance in contrast to Yang and Lee...
Between believing and knowing is a difference and in the last
end such questions must be decided experimentally.

The experiment suggested by Lee and Yang was performed in 1957 by C. S. Wu and collaborators. In this experiment a number of cobalt-60 atoms were cooled down to near absolute zero Kelvin (the lowest possible temperature) and placed in a strong magnetic field. Cobalt-60 is an unstable isotope. Ordinarily, Cobalt-60 decays emitting an electron with any direction equally likely. However, under these extreme conditions, the electrons should be equally likely to emerge from the two poles of the magnetic field – if the fundamental decay process displayed mirror symmetry. Yet, it was observed that more electrons came out from one direction than the other. If we observed only one nuclei decaying we could not say anything. Mirror symmetry does *not* mean that each single interaction or decay process is the same as its mirror image – it is not. Mirror symmetry means that the mirror image process can occur and should occur with equal probability. Therefore, by observing a large number of decays of Cobalt-60 we can easily determine whether mirror symmetry is violated. The remarkable conclusion was that the fundamental laws of physics appear to be ‘left-handed’. This is really very strange. Every other plausible symmetry, such as rotational and translational symmetry, are found to be microscopic symmetries of particle interactions. Can nature really be left-handed?

Are they, the fundamental laws of physics that is, really left-handed or do they only appear to be left-handed? Remember our earlier comments about Lorentz symmetry. At one time this symmetry did not *appear* to be a symmetry at all. This was because anti-matter had yet to be discovered. Only when you have particles and anti-particles is it possible to write down a consistent microscopic theory for the interactions of the electron, proton and neutron which respects Lorentz symmetry. Remarkably, it turns out that it is still possible for particle interactions to be symmetric under mirror

or left-right symmetry. Just as Lorentz symmetry required the existence of anti-matter, left-right symmetry can exist if and only if a new form of matter exists – mirror matter.

Often, it seems that nature is more subtle and beautiful than first imagined. It could be that nature's mirror is of a more abstract kind. Imagine that for each type of ordinary particle there is a separate 'mirror particle'. That is, not only do we have photons, electrons, positrons, protons etc., but also mirror photons, mirror electrons, mirror positrons, mirror protons etc. We can imagine that in nature's mirror not only space is reflected but also particles are reflected into these mirror particles. The relationship between ordinary and mirror matter is somewhat like the relationship between the letters 'b' and 'd'. The mirror image of 'b' is the letter 'd' and the mirror image of 'd' is the letter 'b'. Thus, while neither 'b' nor 'd' is symmetric (in a sense they each have the opposite handedness), together 'bd' is in fact mirror symmetric, with the two letters interchanging in the mirror image⁵. Try it with a mirror and see! Still, the mirror reflection of an object appears very similar to the original. It is perhaps not surprising, therefore, that the properties of the mirror particles turn out to be very similar to the ordinary particles. For example, the mirror particles *must* have the same mass and lifetime as each of the ordinary particles, otherwise the mirror symmetry would be broken.

In some ways mirror particles resemble anti-particles. However, there is a crucial difference. Unlike anti-particles, the mirror particles interact with ordinary particles predominately by gravity only. The three non-gravitational forces act on ordinary and mirror particles completely separately. For example, while ordinary photons (that is, ordinary light) interact with ordinary matter (which is just the microscopic picture of the electromagnetic force), they *do not* interact with mirror matter. Similarly, the 'mirror image' of this statement must also hold, that is, the mirror photon (that is, mirror light) interacts with mirror matter but does not interact with ordinary matter. The upshot is that we cannot see mirror photons because we are made of ordinary matter. The mirror photons would simply pass right through us without interacting at all!

The mirror symmetry does require though that the mirror photons interact with mirror electrons and mirror protons in exactly the

same way in which ordinary photons interact with ordinary electrons and ordinary protons. A direct consequence of this is that a mirror atom made from mirror electrons and a mirror nucleus, composed of mirror protons and mirror neutrons can exist. In fact, mirror matter made from mirror atoms would also exist with exactly the same internal properties as ordinary matter, but would be completely invisible to us! If you had a rock made of mirror matter on your hand, it would simply fall through your hand and then through the Earth, and it would end up oscillating about the Earth's centre^{*}. We can safely conclude that if there was a negligible amount of mirror matter in our solar system, we would hardly be aware of its existence at all. Thus, the *apparent* left-right asymmetry of the laws of nature may be due to the preponderance of ordinary matter in our solar system rather than due to a fundamental asymmetry in the laws themselves.

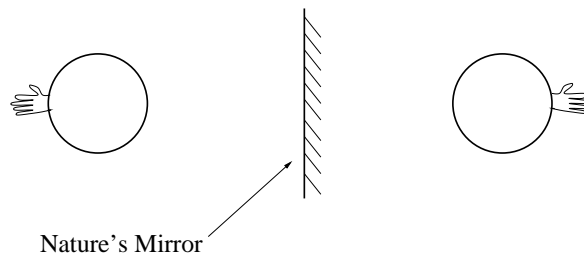
Do mirror particles really make the laws of physics left-right symmetric? Let us consider a simple and light-hearted 'thought experiment' involving again the Cobalt-60 decay. Imagine there was a mirror planet orbiting a mirror star in a distant part of our Universe (note that there is only one space-time – there is no 'mirror Universe'). Let's call this hypothetical planet 'Miros'. Miros is a planet made of mirror matter – atoms composed of mirror electrons and mirror protons and mirror neutrons. Miros is somewhat different to Earth though. It's a bit smaller with deeper oceans, but there is life on Miros. The people of Miros are a bit strange, they have very large feet and only have one eye – but they are very happy. They have wise leaders who would never dream of putting nuclear missiles in space and they realised very early the importance of reducing green house gases. On Miros a football team called 'Collingwood' often wins the football. Thus, Miros isn't much like Earth which just illustrates that microscopic symmetry of particle interactions does not translate into a macroscopic symmetry.

^{*}Later I will discuss the possibility that a *new* type of interaction (or force) could exist coupling ordinary matter to mirror matter. If this is the case, it may actually be possible to pick up a mirror rock, although it would still be invisible. Clearly, the consequences of such a force are very important and it will be considered in chapter 5. However, in order to keep this introductory discussion as simple as possible, this possibility has been ignored.

Anyway, our mirror matter friends on Miros realised the importance of pure science; their wise government always made sure that financial support was given to those mirror scientists who had a research record consisting of interesting and innovative ideas. One day someone on Miros had the idea that they should test whether the fundamental laws of nature are mirror symmetric or not. So they set up their Cobalt-60 experiment with a similar experimental set up as was done by people here on Earth in 1957. But what they found was something quite different. They found the mirror image result. That is, they found that the mirror electrons were mostly emitted from the decaying Cobalt-60 mirror nucleus in the opposite direction as was found here on Earth. Our mirror friends on Miros concluded that the laws of physics were right-handed.

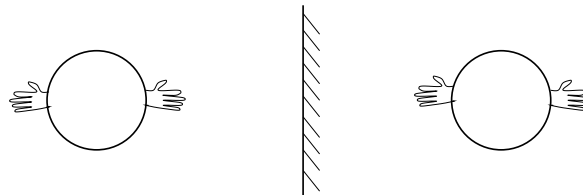
The laws of physics cannot both be left-handed and right-handed. Ordinary particles form a left-handed sector, mirror particles form a right-handed sector. Taken together, neither left nor right is singled out, since ordinary and mirror particles are otherwise identical. (This is much like the letters 'b' and 'd'; 'b' represents the ordinary particles and interactions and 'd' the mirror particles and interactions). However, if mirror particles don't exist anywhere in the Universe then the laws of physics are indeed left-handed. Similarly if the Universe was full of mirror particles with no ordinary ones, then the laws of physics would be right-handed, but if both ordinary and mirror particles exist together then left-right symmetry is restored.

The basic geometric point is illustrated in the following diagram.



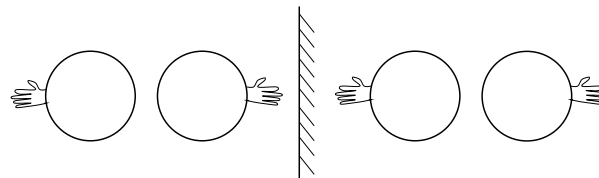
The left-hand side of this figure represents the interactions of the known elementary particles. The forces are mirror symmetric like a perfect sphere, except for the weak interaction, which is represented

as a left hand. Also shown is nature's mirror - the vertical line down the middle. Clearly, the reflection is not the same as the original, signifying the fact that the interactions of the *known* particles are not mirror symmetric. If there were a right hand as well as a left hand then mirror symmetry would be unbroken without the need for new particles:



However, this doesn't correspond to nature since no right-handed weak interactions are seen in experiments.

There are two remaining possibilities: We can either chop the hand off – but this is too drastic and is therefore not shown. It corresponds to having no weak interactions at all, again in disagreement with observations. This last possibility consists of adding an entire new figure with the hand on the other side. Everything is doubled even the symmetric part, which is clearly mirror symmetric as indicated in the following diagram:



It is this last possibility that may correspond to nature.

While the mirror matter theory is simple, elegant, and the idea has been known for a long time, it is only in the past decade that experimental and observational evidence for mirror matter has grown to the point where a strong case can be made that it actually exists – and hence the motivation for this book. The evidence for mirror matter is diverse, ranging from studies of the lightest and most elusive

of the known elementary particles – the neutrinos, to observations of the largest systems – galaxies of stars in the Universe. After reading this book the reader will be aware of the evidence and may make his or her own judgement. At the very least, the question of the existence of mirror matter is one of the most interesting questions in science at the moment, and it should be (hopefully) answered in the next five years.

In the following chapters, I will provide the general picture of how we can find out if mirror matter actually exists and why the case for its existence currently seems so strong. There are broadly two different strategies which can be used to test the theory. First, because mirror matter is stable and behaves much like ordinary matter, it should exist in the Universe today. If one believes that the big bang theory is the correct description of the origin of the Universe, and there is some evidence for that, then mirror matter should have been created along with ordinary matter when the Universe was born. In fact, independently of whether the big bang theory is correct or not, the microscopic symmetry between ordinary and mirror matter suggests that whatever mechanism created ordinary matter should also create mirror matter. In other words, an almost inevitable consequence of the idea that the fundamental laws of physics display left-right symmetry is that mirror matter must exist in the Universe. Furthermore, like ordinary matter, mirror matter can form stars, planets and asteroid sized objects which can populate the heavens. However, such mirror stars, planets and the like would be invisible to us, since mirror matter would only radiate or reflect mirror light which doesn't interact at all with us ordinary people, and our telescopes made from ordinary matter. Thus, the first main prediction of the mirror matter theory is that invisible or dark matter should exist in the Universe.

One might think that invisible dark matter would be unobservable, and this it literally is, however there are simple ways of demonstrating in quite a compelling way that it really exists. In fact, there is a lot of astronomical evidence that the Universe is full of such invisible dark matter. In the following chapters this evidence will be presented and discussed. The evidence not only suggests that most of our galaxy is made of dark matter, but that nearby stars have

mirror planets and even more remarkable, that our solar system contains mirror matter ‘space bodies’ (that is, asteroid sized objects) which are frequently bombarding our own planet Earth.

The other main strategy for searching for the existence of mirror matter is through the implications for microscopic processes such as particle interactions. This is because it is actually possible for *new* small forces to exist, which (like gravity) act on both ordinary and mirror matter. However, because we know that the laws of microscopic particle interactions obey certain symmetries, such as rotational, Lorentz and gauge symmetries, there are only a few possible ways in which small forces can couple ordinary to mirror matter. One possible force is a small coupling of ordinary photons to mirror photons. I will explain in subsequent chapters more precisely what this statement means, however the effect of this tiny force, it turns out, is to make orthopositronium (a weird type of ‘atom’ made from an electron and a positron) decay faster than we would otherwise expect – an effect which has already been observed in an experiment. A more dramatic effect is that it can make mirror matter space bodies visible as they travel through the atmosphere. They may not only be visible but may explode leading to devastating consequences. In fact, the remnants of such cosmic bodies may still be in the ground at various impact sites because the small force between ordinary and mirror matter can be large enough to oppose the force of gravity.

Another way in which microscopic forces can couple ordinary and mirror matter is through a type of ‘mixing’ of neutrinos. Again, I will explain more precisely what this statement means later on, however, the effect of it is to make ordinary neutrinos transform into mirror neutrinos, thereby causing them to effectively disappear. As I will discuss, there is remarkable evidence that neutrinos do indeed disappear, moreover, the rate at which they are observed to disappear is predicted precisely in the mirror matter theory.

Chapter 2

Elementary Particles and Forces

This chapter didn't appear in the first draft of this book. Including too much background material can be dangerously boring. On the one hand, I wanted to get straight into the 'interesting stuff', and on the other hand, some confusion may arise for people unfamiliar with some of the basic concepts. I have therefore included this brief summary of some of the basic 'particle physics' concepts, and also emphasised again how this is extended to include the hypothesis of mirror symmetry. Let me start by sizing up the various scientific disciplines...

Nature's distance ladder

One could define the various scientific disciplines: physics, chemistry, biology, geology, astronomy and cosmology by the characteristic distance size or *scale* involved. The distance scales cover a huge range from one ten million billionth of a centimetre – the domain of particle physics, to distances of order 100 billion light years – the size of the visible Universe. One light year is the distance that light travels in one year which is itself a very large distance – about 10,000 billion kilometres.

Mathematicians are very clever people. They quickly invented

a very simple way of expressing very large numbers and very small numbers. In *scientific notation* large numbers are expressed as powers of 10. For example,

$$\begin{aligned}10^0 &= 1 \text{ (no zeros)} \\10^1 &= 10 \text{ (1 zero)} \\10^2 &= 100 \text{ (2 zeros)} \\10^3 &= 1,000 \text{ (3 zeros)} \\10^4 &= 10,000 \text{ (4 zeros)}\end{aligned}$$

In this notation the size of the visible Universe is 10^{11} light years – or 10^{29} centimetres.

We can also use scientific notation to express very small numbers, like the size of an atom – about one hundred millionth of a centimetre. One hundred millionth is the fraction $1/100,000,000$. In scientific notation, $1/100,000,000 = 1/10^8$ which is conventionally expressed as 10^{-8} . Thus, the size of an atom is simply 10^{-8} cm. With this environmentally friendly paper saving notation, we can conveniently express the characteristic distance scales of nature, see **Figure 2.1**. This figure also illustrates the concept of a logarithmic scale or simply, ‘log’ scale. In a log scale each factor of 10 is equally spaced, but let us not worry too much about that. Instead let’s go straight to the heart of (the) matter.

What is an elementary particle?

It is essentially the same question as asking “what is everything made of?”. Things around us, as well as us, are made of atoms. But what are atoms made of? At one time it was thought that atoms weren’t made of anything, they were indivisible – the basic building blocks of matter. Atoms are about 10^{-8} cm in size. Eventually, it was found that there were even smaller particles. Electrons were discovered (1897-1899), which we now know are point-like down to distances less than about 10^{-16} cm. Not long after that discovery it was proposed that atoms were composed of electrons embedded in a type of jelly, or rather, plum pudding (as the English would have

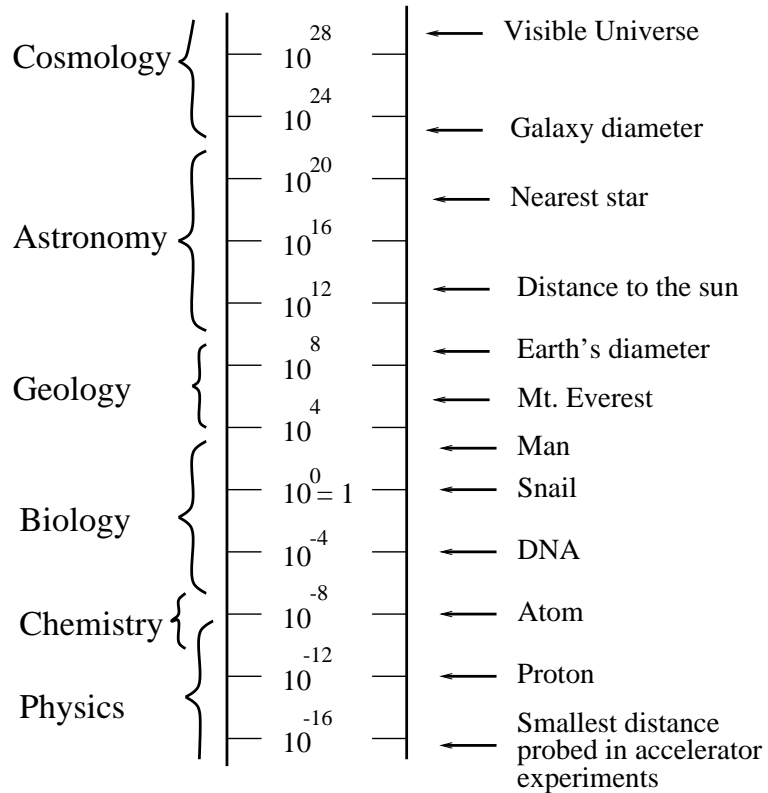


Figure 2.1: Nature's distance ladder (in centimetres).

it) of positive charge. The plum pudding model, as it was known, did not long endure. It was devoured by Rutherford in 1911.

How did Rutherford do it? Early in 1909 Rutherford suggested to two colleagues, Hans Geiger (of 'Geiger counter' fame) and Ernest Marsden to scatter a beam of α particles off a metal foil (α particles are just helium nuclei and are emitted by various radioactive elements). The α particles were very energetic, travelling at about 10,000 km/s. In the plum pudding model, these very fast α particles should just deviate only slightly when passing through the foil – but the experiment suggested otherwise. It was found that a small fraction of alpha particles actually bounced back! This means that the

plum pudding was no ordinary pudding – it suggests that large pips were present. Rutherford later remarked⁶:

It was quite the most incredible event that has ever happened to me in my life. It was almost as incredible as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you.

It took a short time for Rutherford to realise that the implication of these scattering experiments was that the positive charge was not spread out in a pudding, but concentrated at the centre in a ‘nucleus’. Atoms are in fact mostly empty space.

Insight into the rather strange behaviour of electrons in atoms began in 1913 with the Bohr model of the atom. It was found that the traditional or ‘classical’ concepts were completely inadequate to describe the domain of microscopic phenomena. A completely different type of theory was needed. In short, a sort of physics revolution occurred, and by the late 1920’s the quantum theory of the electron had arrived. Ambitious and occasionally even grandiose statements were heard from all quarters. One of the leading physicists of the day, Paul Dirac (the anti-matter man) proclaimed⁷:

The underlying physical laws necessary for the mathematical theory of a large part of physics and the whole of chemistry are completely known.

The structure of the nucleus was also a great problem for many years. Most people thought that it was composed of electrons and protons – but they could never get it to work. Things were greatly clarified by the discovery of the neutron in 1932. The nucleus consisted of protons and neutrons bound together by a new force, called the strong nuclear force.

One important lesson from history is that almost all progress in science is driven by experiments. Pure thought seldom gets very far – unless it is coupled with experiments. Without experiments we might as well sit around in a hot tub and conclude that all matter consists of four elements: fire, water, air, but what’s the other one? I guess it must be earth, but then what are people made of? At this point, I should probably surrender and take out my encyclopaedia, if

I had one, and try to follow the thinking of the ancients. But perhaps this procedure, apparently followed by nearly all writers of popular books on science, is missing the point. Science really began in earnest when people finally got out of their tubs and started to investigate – do careful observations, get their hands dirty and actually do experiments. Sometimes history travels in circles though. There is an interesting recent trend in particle physics. Some people are returning to their hot tubs and arguing that everything is made from ‘strings’ about 10^{-32} cm long which live in 10 dimensional space-time... The idea that the world is a flat plate that sits on a tortoise is in many ways a better theory. It’s a lot simpler and can be tested. Of course, we all know that it cannot explain various established things such as the fact that people who buy round-the-world airline tickets usually return safely. In contrast, string theory appears to have no testable consequences. But that’s another story.

In addition to the protons and neutrons (which together are called ‘nucleons’ since they make up the nucleus) and the electron, one more type of particle was inferred to exist which is called the neutrino. Neutrinos are almost ‘nothing’. They have no electric charge, almost no mass, and interact with the other particles extremely weakly by a new force called the ‘weak nuclear force’. Yet they exist. Indeed at one time it was thought that this was all there was as far as elementary particles were concerned. In 1947 George Gamow published a book (*One, Two, Three... Infinity*) which summed up the situation at that time⁸:

“But is this the end?” you may ask. “What right do we have to assume that nucleons, electrons, and neutrinos are really elementary and cannot be subdivided into still smaller constituent parts? Wasn’t it assumed only half a century ago that the atoms were indivisible? Yet what a complicated picture they present today!” The answer is that, although there is, of course, no way to predict the future development of the science of matter, we have now much sounder reasons for believing that our elementary particles are actually the basic units and cannot be subdivided further. Whereas allegedly indivisible atoms were known to show a great variety of rather complicated chemical, optical, and other properties, the

properties of elementary particles of modern physics are extremely simple; in fact they can be compared in their simplicity to the properties of geometrical points. Also, instead of a rather large number of “indivisible atoms” of classical physics, we are now left with only three essentially different entities: nucleons, electrons, and neutrinos. And, in spite of the great desire and effort to reduce everything to its simplest form, one cannot possibly reduce something to nothing. Thus, it seems that we have actually hit the bottom in our search for the basic elements from which matter is formed.

Before Gamow’s ink could dry, a host of new unstable particles were discovered starting with the muon in 1947, a particle which appeared to have the broad characteristics of a ‘heavy electron’ – about 200 times heavier in fact.

Any physical process that we observe can always be reduced to the microscopic interactions of elementary particles. In a certain literal sense, elementary particles and their interactions are at the ‘heart of the matter’. In the previous chapter, I mentioned that the electromagnetic force saves us from falling through the floor (three cheers for electromagnetism!). This ‘foot feat’ is accomplished by the atoms in our feet repelling against the atoms in the floor – and this is not due to the odour of smelly feet! Electrons don’t have feelings but do have electric charge, and anything with charge is influenced by the electromagnetic force. Like charges repel, opposite charges attract. As the electrons from the atoms in the outer surface of our feet push against the electrons from the atoms on the outer layers of the floor strong electromagnetic repulsion takes effect. This leads to a reaction force which opposes the force of gravity.

Matter Particles and Force particles

At this point it is useful to distinguish between two broad types of elementary particles. ‘Matter particles’ and ‘force particles’. As

we have seen, matter particles consist of the electron, proton, neutron (which are the constituents of atoms) and a less familiar particle called the neutrino. For each of these elementary particles there is a distinct anti-particle (which can also be classified as a type of matter particle).

Even though anti-particles are stable, you can't dig them out of the ground since they would have vanished in a 'puff of light' long ago if there was any initial anti-matter in our solar system (and maybe even in the Universe as well). Nevertheless they exist and play important roles in astrophysics, such as in supernova explosions. There are also a large number of unstable, short lived particles, which have been discovered in the late 1940's and the following decades. Each type of elementary particle has various intrinsic properties such as their mass and electric charge. They also have a certain amount of 'spin'. Roughly speaking, the elementary particles are each somewhat like a spinning top. The matter particles all have the same amount of spin, which in standard units has the value $1/2$, while the 'Force particles' have twice as much spin, that is, they have spin 1.

In the 1960's - 1970's it was realised that the protons and neutrons are not really elementary. They can be viewed as being composed of more elementary constituents called 'quarks'. Quarks were first introduced by James Joyce in his book *Finnegans Wake*: 'Three quarks for Muster Mark'. However, Joyce did not realise that the idea was more universal – not only did Muster Mark get three quarks but every proton and neutron too. This was first conjectured by George Zweig and Murray Gell-Mann in 1963. Gell-Mann's paper was rejected by the Journal *Physical Review Letters* while George Zweig's paper was only distributed as a preprint. The authorities at CERN, where he was working at the time, declared that it was too crazy to be submitted for publication.

What is it about quarks that is so crazy? The problem is that these proton and neutron constituent particles were never seen. If quarks really exist why can't we break open the neutrons and protons and isolate the three quarks? By contrast, the constituent particles of atoms are the electrons, protons and neutrons which can all be isolated. The strange behaviour of quarks was finally understood

when a successful theory of the strong interactions was put together during the early 1970's. This theory suggests that quarks can never be isolated and can only exist in protons and neutrons and also in various other short-lived particles. Fortunately though, for the things that I will discuss in this book, these details are just that, details. We do not need to know anything about the detailed properties of the strong nuclear force (or indeed quarks) except for the fact that it binds protons and neutrons together into nuclei. The properties of the stable matter particles are summarized in Table 2.1*.

Actually free neutrons are not stable, but decay with an average lifetime of about 12 minutes. However, within the nucleus they are quite stable unless the nucleus is radioactive. A radioactive nucleus is one which spontaneously decays after a certain time. There are several types of decay processes, but the one which we will be most interested in is called β -decay.

Matter Particle	Mass $\times c^2$	Electric Charge	Strong Force	Weak Force
Proton (p)	938 MeV	+1	Yes	Yes
Anti-proton (\bar{p})	938 MeV	-1	Yes	Yes
Neutron (n)	940 MeV	0	Yes	Yes
Anti-neutron (\bar{n})	940 MeV	0	Yes	Yes
Electron (e)	0.51 MeV	-1	No	Yes
Positron (\bar{e})	0.51 MeV	+1	No	Yes
Neutrino (ν)	< 5 eV	0	No	Yes
Anti-neutrino ($\bar{\nu}$)	< 5 eV	0	No	Yes

Table 2.1: Some properties of the (stable) matter particles (and the anti-particles).

*The common unit of energy is the electron Volt, or eV. 1 eV is the energy gained by an electron after travelling through a potential of 1 Volt. 1 MeV = 10^6 eV. Also, I have expressed the mass in terms of its energy equivalent through Einstein's famous relation, $E = mc^2$. In this equation, E is the energy, m is the mass and c is the speed of light in vacuum.

In the β -decay process a neutron is converted into a proton and vice versa:

$$\begin{aligned}n &\rightarrow p + e + \bar{\nu} \quad (\beta^- \text{ decay}) \\p &\rightarrow n + \bar{e} + \nu \quad (\beta^+ \text{ decay}).\end{aligned}$$

Fortunately β^+ decay is not observed to occur for free (that is, isolated) protons which can be understood from energy conservation – lighter particles cannot decay into heavier ones. Put more simply, we cannot gain weight without eating. The neutron is heavier than the proton so free protons are quite stable. However, within the nucleus things are more complicated because electromagnetic potential energy can be gained when electrically charged protons are converted into electrically neutral neutrons. For this reason it is possible for protons to decay, but only in certain nuclei. Whether or not a given nucleus undergoes β -decay, and the type of decay (β^+ or β^-) depends on the proportion of neutrons to protons within the nucleus. I will talk a little more about β -decay in a moment, but let me first introduce the notion of a force.

What is a ‘force’? Macroscopically it is a type of intrinsic attraction or repulsion between objects. Without any force an object would move in uniform motion without changing its speed or its direction. Likewise when objects change their speed or direction then this is due to a force. In everyday life, we are aware of many apparently different types of forces: kicking the football imparts a force to the ball, bumping our head on the wall, accelerating in a car, etc. However, microscopically there are only four known ‘fundamental’ forces. They are ‘fundamental’ in the sense that all the other forces result from them at the microscopic level. The four fundamental forces are gravity, electromagnetism, strong and weak nuclear forces. These four forces are further distinguished by the range of their effect. Gravity and electromagnetism are long range forces – they are generally believed to exert their influence over arbitrary large distances. While the strong and weak nuclear forces are observed to be very short range – they only have a measurable effect over microscopic distances. Despite this, microscopically, the forces of electromagnetism, strong and weak nuclear forces are all

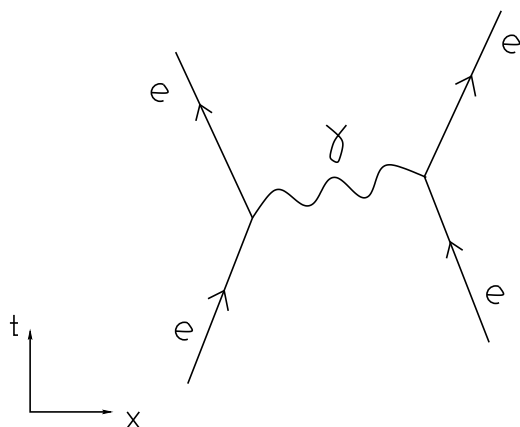


Figure 2.2: Microscopic picture of the electromagnetic force. The electron emits a photon (γ) which causes the electron to change direction. The photon is absorbed by another electron at a later time. In this and in other such diagrams, time (t) runs up the page and distance (x) runs across the page.

fairly well understood. Each force can be microscopically described in terms of the action of a ‘force particle’.

Taking the electromagnetic force for example, microscopically the fundamental process involved is the interactions of electrons and protons with photons. The photon is the force particle for electromagnetism. Considering the electron, it has, at any give time a certain chance of emitting a photon. This ‘interaction’ causes the electron to change direction and speed if the photon is eventually absorbed by another distinct matter particle. This can be viewed diagrammatically as shown in **Figure 2.2** above.

This type of diagram was first used by Richard Feynman in the 1940s. In the technical literature this type of diagram is called a ‘Feynman diagram’, but in this book I will use more descriptive language and call it an ‘interaction diagram’. Anyway, microscopically the electromagnetic force results from photon-electron interactions.

This is the fundamental process behind the force of electromagnetism. Actually things are slightly more complicated because the exchanged photon in Figure 2.2 is not exactly the same as a real photon – it is called a ‘virtual photon’ in the technical literature. Again though, we don’t need to bother too much about technical details such as this.

Broadly speaking, the weak and strong nuclear forces are similar to electromagnetism, but they each have certain important differences as well. Considering the weak interactions, there are not one but three force particles called W^+ , W^- , Z^0 . These particles were first predicted to exist in 1961 and finally discovered in an experiment in 1983. One interesting thing about W^\pm particles is that when they are emitted or absorbed they always change the identity of the matter particle. For example, consider the β -decay process of the decay of a proton in the nucleus: $p \rightarrow n + \bar{e} + \nu$, which can be viewed diagrammatically as shown in **Figure 2.3** below. As the diagram illustrates, the proton is converted into a neutron as it emits a W^+ particle, which later turns into a positron and a neutrino.

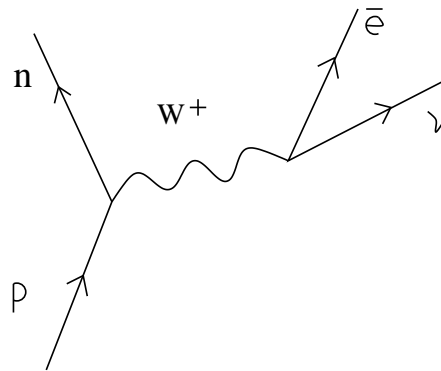


Figure 2.3: Microscopic picture of β -decay. The proton (p) is transformed into a neutron (n) by emitting a W^+ . The W^+ then transforms into a positron (\bar{e}) and a neutrino (ν).

Turning now to the strong nuclear force, the protons and neutrons exchange not three but eight force particles called gluons. There are additional complications since these gluons are believed to interact with the point-like particles called ‘quarks’ within the protons and neutrons. Fortunately, complicated details such as this need not concern us at all since we only need to be aware that the strong interactions bind the quarks into nucleons and it also binds nucleons into nuclei. Nuclei of course can combine with electrons via the electromagnetic force to form atoms. Atoms can combine together to form molecules (also via the electromagnetic force) and molecules can combine together to form you and me. But of course we are perhaps more than a bunch of atoms...

The ‘force particles’ are summarized in the table below.

Force	Force particle
Electromagnetism	γ (photon)
Weak Nuclear Force	W^{\pm}, Z^0
Strong Nuclear Force	G^a (Gluons)

We don’t need to know much about these details. The reader only needs to be aware that the old but good idea of forces can be viewed microscopically as due to the exchange of force particles, and that the force particle for electromagnetism is just the photon, the photon is of course the particle which makes up ordinary light.

One final comment is that gravity is not well understood microscopically. It is tempting to postulate the existence of a force particle for gravity – called the ‘graviton’, but the fine details are not known. What is known is that gravity is quite different from the other forces. How to reconcile gravity with microscopic physics is a deep mystery. Luckily, we don’t need to worry too much about this because we only consider the effects of gravity on large objects such as asteroids, planets and stars etc. For such large objects Newton’s or Einstein’s ‘classical’ theory of gravity suffices. I will talk more about Newton and Einstein later, but for now let’s return to the microscopic particle interactions of the non-gravitational forces.

Mirror Particles and Mirror Forces

The idea of mirror matter arises from the interactions of the elementary particles. These interactions are known to possess many symmetries, but the most obvious symmetry of all, left-right or mirror symmetry, is not a symmetry of the *known* elementary particles. The weak nuclear force is the culprit which is, in a sense, left-handed. As discussed in the previous chapter, this remarkable fact was first demonstrated in 1957 using β -decay experiments.

This apparent left-handedness of the fundamental laws of physics is particularly striking for neutrinos. The neutrino is an elusive elementary particle which is emitted along with the positron (or electron) in β -decay. As I have already mentioned, β -decay can be viewed as the elementary process of proton (or neutron) decay within radioactive nuclei (such as Cobalt-60), $p \rightarrow n + \bar{e} + \nu$. Like most elementary particles, such as the electron or proton, the neutrino always has a certain amount of ‘spin’. I have already mentioned that this means that each electron can be viewed, roughly speaking, as a ‘spinning top’. Spin is an intrinsic property like mass or charge. Every neutrino, electron or proton, always has the same amount of spin, although it may point in different directions.

A remarkable observation though is that in β -decay, or any other process that produces neutrinos, the neutrinos (ν) *always* have their spin axis orientated in the same direction relative to their direction of motion. If the neutrino were coming towards you, you’d see it spinning clockwise, in other words, it twists like a left-handed corkscrew. Just as a clockwise spinning top becomes an anti-clockwise spinning top if viewed in a mirror, the left-handed neutrino becomes a right-handed one when viewed in a mirror (see **Figure 2.4** on the following page). Thus, mirror symmetry would suggest the neutrino should be emitted with a right-handed spin half of the time. Yet, nobody has ever observed a single right-handed neutrino. In contrast, anti-neutrinos are *always* observed to be right-handed.

In the introduction I pointed out that the fundamental interactions of nature could exhibit mirror symmetry only if a set of mirror particles exist. One might wonder, though, whether mirror particles

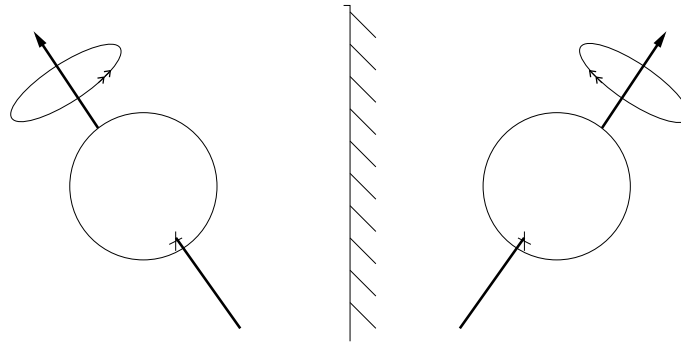


Figure 2.4: A clockwise spinning top (or left-handed neutrino) becomes an anti-clockwise spinning top (or right-handed neutrino) when viewed in a mirror.

are really necessary. Could nature's mirror reflect particles into anti-particles as well as reflecting space? This seems possible because all neutrinos are observed to be left-handed while all anti-neutrinos are observed to be right-handed. Such mirror symmetry would have many other implications. For a while this idea appeared to work. The anti-particle processes did appear to behave like the mirror image of the ordinary particle processes. However, this anti-matter mirror was shattered after just seven years. In 1964, an experiment demonstrated that this type of mirror was also broken.

The 1964 experiment involved a rather strange short lived particle known as a kaon. Because kaons live only a very short time before they decay – less than a millionth of a second – they may seem quite unimportant. Nevertheless they exist and their interactions must display the symmetries of nature, whatever they happen to be. Indeed, our current understanding of elementary particles not only describes the stable particles such as the protons and electrons, but also strange short lived particles (of which there are many) such as the kaons. Anti-kaons also exist and are distinct particles. The 1964 experiment demonstrated that kaons do not display left-right

symmetry even when kaons are also reflected into anti-kaons. This amounts to nothing less than the apparent breakdown of any form of left-right symmetry in nature – or does it? The prospect that the most natural symmetry imaginable – mirror symmetry – is not a symmetry of nature, while every other obvious symmetry such as rotational symmetry and translational symmetry are indeed symmetries seems rather surprising to say the least.

Remarkably though, as I mentioned in the previous chapter and will expand upon here, it turns out that it is still possible for particle interactions to exhibit also mirror symmetry if a new form of matter, called ‘mirror matter’ exists. As just discussed above, having our mirror reflect particles into anti-particles as well as the mandatory space reflection simply doesn’t work. It was a logical possibility but it didn’t agree with experiments. If it doesn’t agree with experiments it can’t describe nature. Instead, imagine having a mirror that reflects every particle (including their anti-particles) into a completely new type of particle – which we might call a ‘mirror particle’. In other words, I am proposing that for each type of ordinary particle, such as the photon, electron, positron, proton, anti-proton etc., there is a corresponding mirror particle *which is a distinct physical particle*.

This type of mirror seems a bit different to the one in your bathroom, since bathroom mirrors do not change the identity of the particles, or do they? Actually though, your bathroom mirror changes left-handed particles into right-handed ones, so the reflected image is, microscopically or ‘quantum mechanically’, composed of different particles or ‘states’. It is therefore an *a priori* possibility that nature’s mirror could reflect ordinary particles into distinct mirror particles. This mirror is illustrated in **Figure 2.5** (on the following page) with the mirror particles being distinguished from the ordinary ones with a prime (’).

The mirror symmetry interchanges the ordinary particles with the mirror particles as well as reflecting space, so that the properties of the mirror particles completely mirror those of the ordinary particles. This means that the mirror particles *must* have the same mass and lifetime as each of the ordinary particles otherwise the mirror symmetry would be broken. It also means that while the ordinary

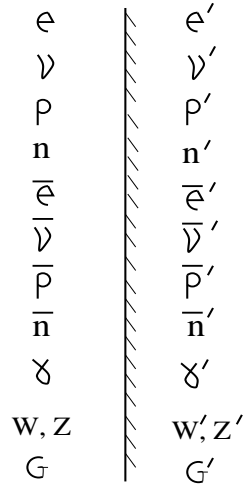


Figure 2.5: Nature's mirror might reflect each ordinary particle into a distinct mirror particle.

particles appear in certain processes to be left-handed, the mirror particles appear in the corresponding mirror processes to be right-handed. For example, the β -decay process,

$$p \rightarrow n + \bar{e} + \nu_L$$

where the 'L' reminds us that the neutrino is observed to be always left-handedly spinning, implies the existence of the 'mirror image' process

$$p' \rightarrow n' + \bar{e}' + \nu'_R$$

with the mirror neutrino spinning right-handedly.

Importantly I assumed that each of the force particles also has a distinct mirror partner. This is a crucial assumption and it is necessary to explain why mirror particles are not produced in laboratory experiments. Ordinary particles interact with other ordinary particles through the exchange of ordinary force particles. Similarly, mirror particles interact with other mirror particles through the exchange of mirror force particles. There are no 'cross interactions'

connecting ordinary and mirror particles from any of the known non-gravitational forces*.

Clearly, just as ordinary atoms can form by the electromagnetic force between protons and electrons, mirror atoms can form by the mirror electromagnetic force between mirror protons and mirror electrons. However, ordinary and mirror atoms do not interact with each other – except by the very feeble gravitational force. Thus, if there was a rock made of mirror matter in front of our eyes then we couldn't see it because it doesn't emit or reflect ordinary light. It could emit mirror photons if it was hot but mirror photons would pass right through us without interacting. Conversely, if we shone ordinary light on it then the ordinary photons would just pass through it. As I already mentioned in chapter 1, we couldn't pick it up because it would simply fall through our hand under the force of gravity and then through the Earth (assuming here that there are no new interactions connecting ordinary and mirror matter, see the previous footnote). We can safely conclude that if there was a negligible amount of mirror matter in our solar system we would hardly be aware of its existence at all.

Another way of illustrating the consequences of the mirror symmetry connecting ordinary and mirror particles is by considering the following 'thought experiment'. I already discussed one such thought experiment in the introduction – about a distant mirror planet called Miros. Now imagine that there is a wizard more powerful than Harry Potter, so powerful in fact that he could easily change every particle in our entire solar system into mirror particles. Would we notice? We would still be here but made of mirror atoms instead of ordinary ones, gravity would hold our feet down, mirror electromagnetism would stop us from falling through the floor (made of mirror matter) and the Sun would produce energy via the mirror nuclear force which would be converted into mirror light via mirror electromagnetic interactions. The only observable difference would be that

* Actually, later on in chapter 5 I will discuss the possibility of tiny *new* forces connecting the ordinary and mirror particles. However, these are new forces which are completely independent from the four known forces. For the purposes of this preliminary discussion a detailed examination of possible small forces connecting ordinary and mirror particles is ignored.

the stars in the night sky would look different – if we are made of mirror matter we would see mirror stars instead of the ordinary ones. Thus, assuming that there are both ordinary and mirror stars in the sky, we would see a different set of stars if we were made of mirror matter. The only other difference would be that in β -decay the mirror neutrinos would all be right-handed instead of left-handed...

Whose crazy idea?

Scientists often amuse themselves by arguing about the priority of ideas – everyone needs a hobby! Who did what, when. In the 17th century Newton and Leibniz had lots of fun arguing about who really discovered calculus. In the case of mirror matter the idea should date from sometime after 1956, since before this everyone generally assumed that the fundamental interactions were already mirror symmetric so there would have been no reason for postulating the existence of mirror matter. It is somewhat surprising to learn that the idea of mirror matter didn't take long to be proposed. The idea first appeared in the scientific literature in 1956, the same year that it was suggested that the ordinary interactions did not respect left-right symmetry. In fact, not only in the same year, but also by the same authors (Lee and Yang) and also in the same paper! While the Lee and Yang paper was devoted to arguing that left-right symmetry may be broken by the weak interactions of the ordinary particles, the last two paragraphs suggested that it could be unbroken if mirror matter existed. In the words of Lee and Yang (from their 1956 paper⁹):

As is well known, parity* violation implies the existence of a right-left asymmetry. We have seen in the above some possible experimental tests of this asymmetry. These experiments test whether the present elementary particles exhibit asymmetrical behaviour with respect to the right and the left. If such asymmetry is indeed

* Authors Note: 'parity' is another term used in the technical literature to describe mirror symmetry. 'Parity violation' means 'violation of mirror symmetry'.

found, the question could still be raised whether there could not exist corresponding elementary particles exhibiting opposite asymmetry such that in the broader sense there will still be over-all right-left symmetry. If this is the case, it should be pointed out, there must exist two kinds of protons p_R and p_L , the right-handed one and the left-handed one. Furthermore, at the present time the protons in the laboratory must be predominately of one kind in order to produce the supposedly observed asymmetry,.....

In such a picture the supposedly observed right and left asymmetry is therefore ascribed not to a basic non-invariance under inversion, but to a cosmologically local preponderance of, say, p_L over p_R , a situation not unlike that of the preponderance of the positive proton over the negative. Speculations along these lines are extremely interesting, but are quite beyond the scope of this note.

Lee and Yang never returned to the mirror matter idea and were content with receiving the Nobel prize for their work suggesting that mirror symmetry was broken. In fact, the idea was largely forgotten with only a handful of papers written on the subject during the following three decades. My colleagues, Henry Lew, Ray Volkas and I, blissfully unaware of the last two paragraphs of Lee and Yang's paper, rediscovered the idea in 1991 and put it into a modern context. More recently, Zurab Silagadze also rediscovered the idea while reading the 'Encyclopaedia of Anomalous Phenomena' – I'll have to get a copy of that book! I have also been told by a kind Professor from India that the idea first appeared several thousand years ago in the ancient book the 'Upanishads'.....

In physics many seemingly simple and elegant ideas are proposed only to be eventually discarded when they are carefully checked by experiments and observations. This is something which distinguishes science from other disciplines. The fate of the mirror matter theory therefore rests with experiments and astronomical observations – it cannot be decided by pure thought. It is time now to examine the evidence....

*It's good to have an
open mind, but not so open
that your brains fall out.*

Bertrand Russell

PART II

Evidence for Mirror Matter in the Universe

Chapter 3

Discovery of Mirror Stars?

If mirror matter really does exist then it is reasonable to suppose that it exists in our galaxy and in other galaxies. Yet, because it is invisible, neither emitting nor reflecting ordinary light, it would be completely dark. This does not mean, though, that it cannot have observable consequences because even invisible dark matter can make its presence known to us by its gravitational effects. A famous historical example of the power of gravity is the discovery of our 8th planet, Neptune.

The discovery of Neptune

The first six planets have been observed since ancient times. The 7th planet, Uranus, was discovered by the English astronomer William Herschel in 1781 using a homemade reflecting telescope. Prior to the discovery of Uranus, the most distant known planet was Saturn, which orbits the Sun at a distance of about 1.4 billion kilometres – nearly 10 times the distance at which the Earth orbits the Sun. Uranus, it turns out, orbits at a distance of about 2.9 billion kilometers, taking approximately 84 years to complete an orbit around the sun.

The 8th planet Neptune was discovered 65 years later, but unlike Uranus, whose discovery was accidental, the discovery of Neptune was no accident. Indeed, Neptune's discovery is a rather impressive example of the power of the scientific method. This discovery is illustrated in **Figure 3.1**.

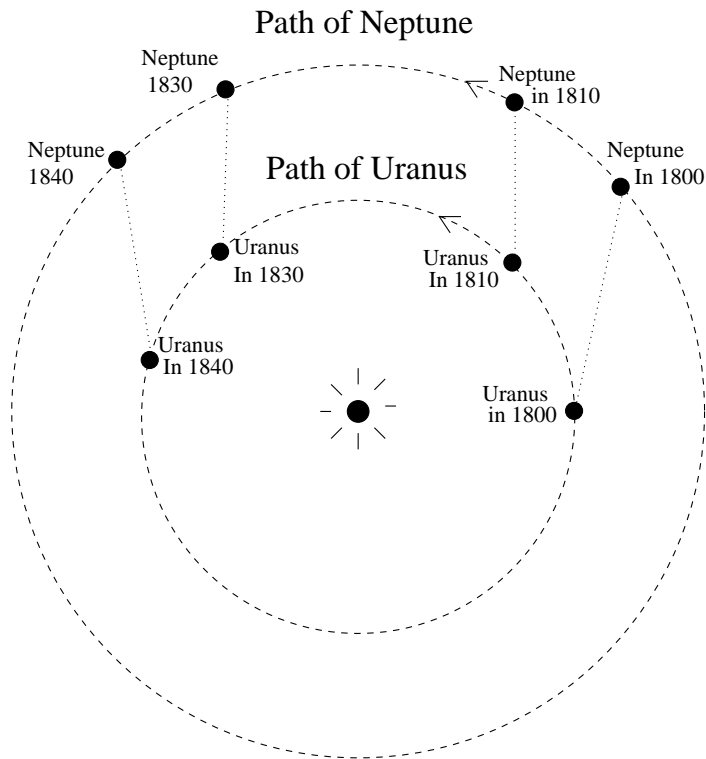


Figure 3.1: The relative positions of Uranus and Neptune during the period 1800-1840. Between 1800-1810 Uranus was moving towards Neptune and the gravitational influence of Neptune caused Uranus to travel faster. While between the years 1830-1840 Uranus was moving away from Neptune and the gravitational influence of Neptune caused Uranus to travel slower.

Newton showed us how to calculate the orbits of the planets. Put another way, they must obey Newton's laws of motion. However, Herschel's discovery of the 7th planet Uranus eventually led to something odd. Its orbit did not follow exactly the expectations from Newton. This means that either a) Newton's laws were somehow wrong*, b) there were mistakes in the observations of Uranus,

* Actually, Einstein showed much later that they do in fact break down under certain conditions, but this was not the reason for the anomalies in Uranus's orbit.

or c) there was something new. In October 1845 the Englishman John Adams and independently on the other side of the channel Urbain Leverrier (in June 1846) proposed that an hitherto unseen planet (Neptune) must exist further from the Sun. Not only did they predict that it must exist, but the mathematics through which physical laws are described allowed them to predict its position very accurately. In fact, the two independent calculations of Adams and Leverrier agreed with each other to within 1 degree for their positioning of Neptune.

John Adams was spectacularly unsuccessful at convincing the astronomers to search for Neptune – they either didn't understand his calculations or didn't bother to. Leverrier's efforts met with more success. The night after receiving a letter from Leverrier suggesting that he should look for the new planet, Johann Galle of the Berlin Observatory found Neptune in September 1846. But Galle's job was made easy for him – he was told where to look. Clearly, Neptune made its presence known first by its gravitational effects and was later observed directly. Galle's boss, Johann Encke, who initially thought that the search was a wild goose chase (or in the case – 'planet chase') wrote to Leverrier¹⁰:

Allow me, Sir, to congratulate you most sincerely on the brilliant discovery with which you have enriched astronomy. Your name will be forever linked with the most outstanding conceivable proof of the validity of universal gravitation...

Of course, in books such as this, authors such as myself are always wheeling out successful historical examples. The reader should be aware that for every theoretical success there are also many failures. The failures, however, are not usually emphasised and are often quickly forgotten*. Still, the successful cases do show

*One such 'failure' which has not quite been forgotten is the story of the planet 'Vulcan'. Buoyed by his 'discovery' of Neptune, Leverrier went on to argue that a new planet – Vulcan – was required to explain an anomaly in the orbit of Mercury. Searches for Vulcan failed to find it, or rather, many searches found it, but it was never confirmed. The anomaly was later explained by Einstein in 1915; Mercury's orbital misbehaviour was not due to a new planet or due to mistaken observations, but due to the modification of gravity predicted by Einstein's general relativity theory.

that at least sometimes people get things right. With this cautionary note in mind, let me now continue the story.

Distribution of matter in the heavens

In the Universe matter is not uniformly distributed. From observations we know that matter bunches together to form stars, stars bunch together to form galaxies, and galaxies bunch together to form galaxy clusters. This is our current picture of the observable Universe. Exactly how the Universe came to be like this is certainly an interesting but very difficult problem. It is a problem which is at the forefront of modern research. Needless to say it is even now not understood and that's *why* it's at the forefront of modern research. Fortunately, the most compelling arguments for the existence of mirror matter in our galaxy are essentially observation based. They do not require knowledge of the physics of galaxy formation or complete understanding of the evolution of the Universe from its beginning, assuming it has one, to the present time. Of course, such knowledge would be very useful, but we can learn much without it.

Newton's laws of gravitation are simple and powerful. Anything with mass will influence the motion of any other body with mass. The influence is greater the closer the two bodies are. Equally important is that the effects of gravity are greatest for bodies of larger mass. Of course this effect is well known to Moon walkers. Neil Armstrong could jump higher on the Moon than on the Earth. This was not just because of his great joy at being the first person on the Moon, or because he had just bought a Toyota. Rather, it was simply because the force of gravity on the relatively light Moon is much less than the relatively heavy Earth.

There is good reasons to believe that gravity is universal. The orbits of the Moon and man-made satellites around the Earth, the orbits of the planets, comets and asteroids around the Sun all obey the same universal law. Indeed, the power of Newton's laws has been quite spectacularly demonstrated with our discussion of Neptune. What about on very small distances? Small distance scales can be studied in careful laboratory experiments using a type of pendulum

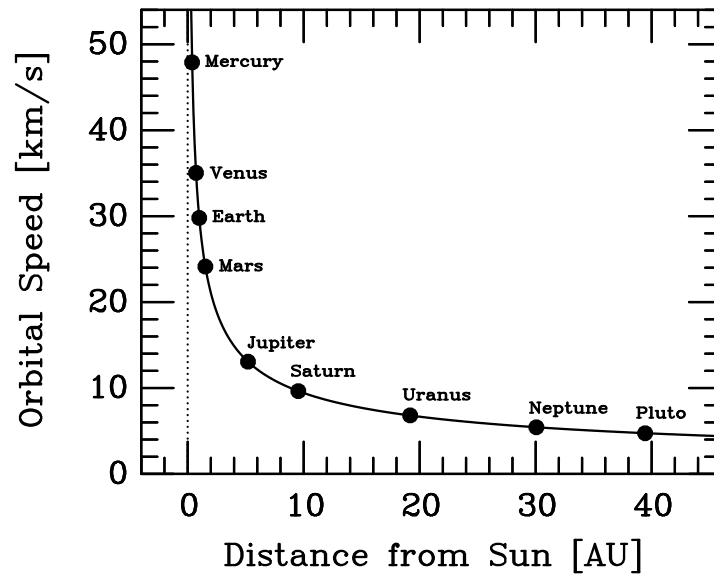


Figure 3.2: Orbital speed of the planets versus their distance from the Sun.

called a ‘torsion pendulum’. Such experiments have confirmed that gravity is described by the same rules on very short distances as it is over large distances. For example, a recent laboratory experiment¹¹ has measured the gravitational attraction between objects just 0.2 millimetres apart, again showing that Newton’s laws are upheld.

The gravitational force on the planets is due mainly to the mass of the Sun. This is because the Sun contains more than 99% of the mass of the solar system. The closer a planet is to the Sun, the greater the gravitational attractive force which the planet feels. The larger the force, the larger is the planet’s orbital velocity. Conversely, the more distant the orbit the weaker the hold of gravity, which means that distant planets must move more slowly otherwise they would be flung into space never to return. **Figure 3.2** (above) shows how the orbital speed of the planets varies from their distance to the Sun. [The unit of distance is the Astronomical Unit or AU.

1 AU is the Earth-Sun distance]. As the figure shows, the velocity ranges from about 50 km/s for our closest planet – Mercury, to about 5 km/s for our most distant known planet – Pluto.

Evidently, there is a strong connection between orbital velocity and the force of gravity. In fact, knowing Newton's laws we could put constraints on the distribution of mass in our solar system by studying the orbits of the planets and the other orbiting bodies such as comets and asteroids; the mass distribution directly affects the gravitational force which dictates the orbital motion of the planets. For our solar system there is not much room for a large proportion of invisible mirror matter, or any other type of invisible matter. Any nearby mirror matter planet in our solar system would have made its presence known via its gravitational effects on the motion of the other planets or comets, in much the same way that Neptune's existence was revealed from its gravitational effect on the motion of Uranus.

Nevertheless, small bodies (for example, asteroid or comet sized objects) made of mirror matter are possible because the gravitational influence of these bodies would be far too small to have been detected. Also, a planetary or even star sized mirror object is also possible if its orbit is distant enough. In fact, in chapter 6 I will discuss fascinating evidence that there are indeed mirror matter objects out there in our solar system. There is explosive evidence that small asteroid or comet sized mirror matter objects exist and occasionally collide with the Earth as well as independent evidence for planet or star sized mirror matter objects in distant orbits from the Sun.

In any case, within the orbit of Pluto there is not much room for a large amount of mirror matter. Let us move on to larger distances. If we were to look at our solar system from a great distance away – so great that our solar system appeared as a tiny point source of light, then we would notice that it is also in motion. It is orbiting around the centre of our galaxy in a roughly circular orbit. The huge distance involved means that it orbits the centre of the galaxy only about once every 200 million years. If we move even further away, such that our galaxy was only the size of a bright point, then our solar system would be in motion around the neighbouring galaxies.

But before we go away any further, let us come back a step. While I have argued that there is no evidence for a large amount of mirror matter in our solar system (although later I will argue that there is interesting evidence for a small amount), what about on larger distance scales? Could there be a large amount of mirror matter in our galaxy? One might think that because Newton tells us there cannot be much mirror matter in our solar system, it follows that there cannot be much mirror matter in our galaxy. Still, we must be careful, the galaxy is so much larger than the solar system. It might be possible for ordinary and mirror matter to be distributed quite independently; a sort of cosmic segregation, a bit of ordinary matter here, a bit of mirror matter there...

Actually, it turns out to be very easy to understand why ordinary and mirror matter should be separated on relatively small distance scales like our solar system. However, I will postpone a discussion of this for later. In the meantime one could just keep in mind the possibility that the distribution of mirror matter and ordinary matter can depend very much on the distance scale involved. In fact, as just about any ancient person from Mongolia or Tibet would surely have testified, because their nearby region contains only land and they and nobody else they knew ever saw any oceans, the whole world must be made of land... They might have been surprised to discover that the Earth's surface is covered by more than 70% ocean...

Galaxies contain an invisible spherical halo of dark matter

It is now time to take a closer look at our own galaxy – The Milky Way. Our galaxy appears to be a typical spiral galaxy containing of order 100 billion stars which are distributed in a flat disk, with a small spherical bulge at the centre. Obviously (with current technology) we can't view our entire galaxy from a distance, but we can take pictures of other similar galaxies. **Figure 3.3** (on the following page) shows pictures of three typical spiral galaxies with different orientations.

Just like the mass distribution in our solar system could be determined by looking at the motions of the planets around the Sun, we can determine the mass of the galaxy, as well as obtaining information about the distribution of mass within the galaxy, by measuring the velocity of stars at various locations and distances from the galactic centre. We might expect that most of the mass is near the central region of the galaxy because that's where most of the light is. If this were the case then our galaxy would be dynamically similar to our solar system – but on a much larger scale. This means that the orbits of stars should show a significant *decrease* in their orbital velocity as one observes stars orbiting further and further from the galactic centre. Surprisingly though this is not the case. In fact, the velocity is more or less constant as one looks at objects with larger and larger orbits (**Figure 3.4**¹²). This is true of stars at the edge of the disk as well as stars and compact groups of stars called 'globular clusters' distributed out of the plane of the disk.

The conclusion is that there is much more to our galaxy than meets the eye. And this is in fact literally true. The mass and distribution of light emitting/reflecting matter is completely different to the mass and distribution of matter inferred dynamically from the effects of gravity through Newton's laws. The upshot is that our

FIGURE 3.3

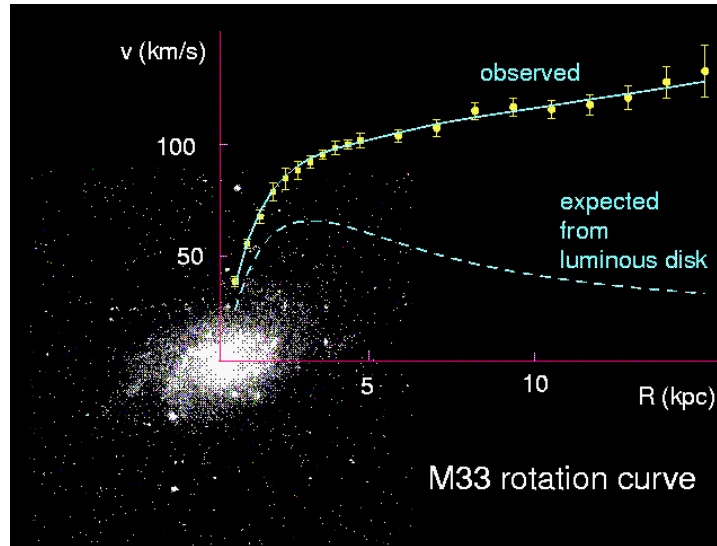


Figure 3.4: Observed orbiting velocities of stars (vertical axis) in the spiral galaxy M33, superimposed on its optical image. The horizontal axis is the distance from the centre of the galaxy in kiloparsecs (1 kiloparsecs is 3.3 thousand light years). The poor agreement between the expected velocities and the actual ones provides strong evidence for invisible ‘dark matter’.

galaxy (and similar results have also been found for other galaxies) extends well beyond the visible edge. Even more interesting is that the mass is distributed spherically, roughly like a (3-D) sphere or ball, which is called the halo, despite the fact that the visible mass is predominately distributed in a flat disk.

Although this invisible mass distribution is called a ‘halo’, it is not much like the halo around the heads of the saints. Rather, it is a three dimensional spherical distribution which starts from the galactic centre and extends beyond the visible edge of the galaxy. The amount of mass in this three dimensional halo is estimated to be at least several times the amount of mass in the disk. Thus, in the

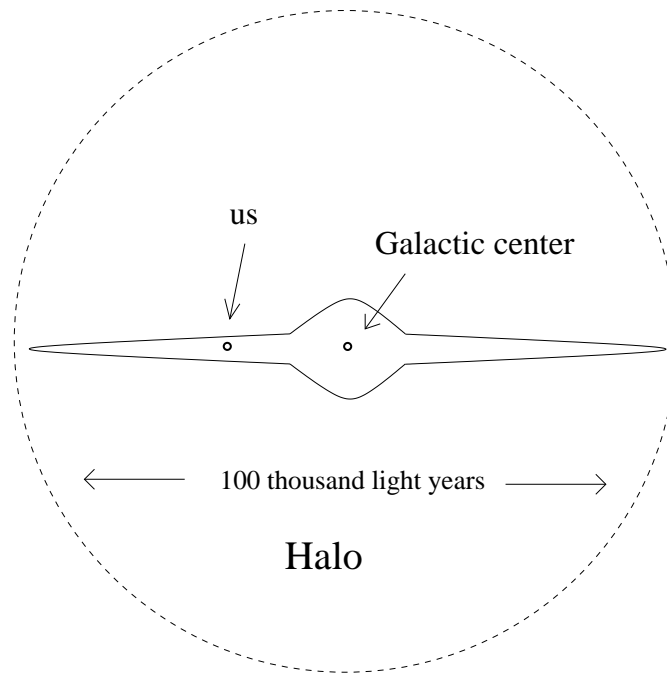


Figure 3.5: Inferred distribution of mass in our galaxy. The visible matter forms a disk, viewed edge-on in this figure, which is surrounded by an invisible three dimensional spherical halo of matter.

case of galaxies, what we see is *not* what we get. The inferred mass distribution of our galaxy is illustrated in **Figure 3.5** (above).

This result is not something that was found yesterday or even the day before. The evidence has built up over many decades; it is not even conceivable that the results could be due to mistaken observations. The observations have been repeated by many independent groups in many countries for many galaxies, all reaching the same embarrassing conclusions. We may therefore say with some certainty that either invisible dark matter exists or Newton's laws are wrong.

We know that Newton's laws cannot be completely wrong. They

have been verified for objects in our solar system with tremendous accuracy. The only known examples (in our solar system) where they breakdown are a tiny anomaly in the motion of Mercury and also the bending of light around the Sun. However, both of these examples are completely understood and were explained, or in the case of the bending of light around the Sun, predicted by Einstein in 1915. Einstein's theory of gravity goes by the title of 'general relativity'. General relativity is *not* simply a modification of Newton's laws, but a very different sort of theory. However, Einstein's general relativity theory does agree with Newton's theory when the gravitational force is not too strong, as is almost always the case in most practical examples. For this reason, Newton's laws are considered today as a very useful *approximation*. In the case of stars orbiting around the galactic centre, Einstein's theory gives the same results as Newton.

Of course, it is possible to imagine that both Newton and Einstein are wrong. Nobody is perfect. Maybe these theories only work over relatively small distances such as the size of our solar system – a mere few billion kilometres, while over larger distances they become modified in such a way to explain the motions of the stars in our galaxy without any embarrassing invisible matter. Certainly this is possible, but so far nobody has managed to find a very elegant theory which does this. Obviously, the non-existence of such a theory cannot be rigorously shown either. Nevertheless, at the present time, the most reasonable interpretation of the observations seems to be that invisible dark matter really does exist, and in fact dominates the mass of our galaxy.

The nature of the beast

If we accept that invisible dark matter really does exist, then the next logical question to ask is what is the nature of this dark matter? Is it something standard made of ordinary matter? Maybe it is in the form of faint dead stars called 'white dwarfs' or small stars that never get hot enough to burn hydrogen called 'brown dwarfs' ? Or is it something else, something more exotic?

While some of it is surely in the form of dust and gas this cannot explain the inferred dark matter in the halo. Astronomers have been able to gather information on the overall distribution of dust and gas within our galaxy by measuring the effects of the absorption of star light and by tell-tale radio (wavelength) emissions. They conclude that dust and gas contribute a negligible amount to the galactic halo, although there may be a significant component in the disk. In fact, every conventional possibility for the dark matter runs into serious problems for one reason or another.

As another example, let me briefly mention white dwarfs. White dwarfs are faint dead stars which have used up all their nuclear fuel and no longer sustain nuclear reactions. Our sun is destined to become a white dwarf one day. Currently, it is a middle aged star with no mid-life crises in sight so we don't have to worry too much at the moment. Anyway, when a star stops burning nuclear fuel its central pressure is no longer great enough to support its huge weight. The effect of this is that the star becomes gravitationally unstable. The inner part of the star collapses under its own weight with a white dwarf as the end product. Typically a white dwarf has a size as small as the Earth but with a mass comparable to that of the Sun.

Initially white dwarfs are quite hot, but since they are no longer burning nuclear fuel and producing energy, they slowly cool. However, because they are so small they are very faint. Indeed, their luminosity is proportional to their surface area which is about 10,000 times smaller than an ordinary star like our Sun. Because of their extreme faintness they can only be observed in the very nearby region of our galaxy, typically less than a few hundred light years from us (although, the youngest and hottest white dwarfs can be seen significantly further away than this). The population of white dwarfs could therefore be very numerous – perhaps numerous enough to account for the mysterious invisible mass in our galaxy. Still, there are very big problems with this idea despite its obvious merits.

The main problem with 'white dwarf dark matter' is that in the collapse process where they are formed, the outer layers of the star are ejected into space. This would lead to observable consequences which are not seen. For instance, I already discussed the fact that observations appear to exclude any significant amount of gas or dust

in the halo of our galaxy. Even if the ejected gas collapses onto the galactic disk due to collisional processes, its estimated abundance would be greater than the entire inferred mass of the disk. Furthermore, this ejected material is rich in heavy elements such as carbon and nitrogen (in astrophysics any element heavier than helium is called a ‘heavy element’) which do not seem to be particularly abundant in our galaxy.

Other possibilities for the halo dark matter, such as black holes and neutron stars, suffer similar problems since their formation also leads to heavy element pollution and other tell-tale signs. In fact, *every conventional candidate for the dark matter is in serious conflict with observations*. Not surprisingly then, the mysterious nature of the dark matter is widely considered as the greatest of all puzzles in astrophysics at the moment.

At the end of the day we are left with the remarkable conclusion that, not only is most of the mass in galaxies invisible, but galaxies it seems are not predominately made from ordinary matter at all. Galaxies seem to be predominately made from something completely unknown, something that is, in a very literal sense, not of this world...

Enter mirror matter

Imagine that a significant part of our galaxy was indeed made of mirror matter. Could that explain the mystery of the inferred dark matter? Clearly mirror matter is dynamically very similar to ordinary matter, it would form stars, planets etc., but would not emit any ordinary light. It would emit mirror light (that is, mirror photons), but we can’t detect that. In short it would be invisible – which is just what’s required. So far so good. But what about the distribution? Because ordinary and mirror matter only interacts with each other via gravity, their distribution can be completely different (depending on their initial conditions such as chemical composition and angular momentum). But could this really explain why mirror matter doesn’t form in a disk like ordinary matter?

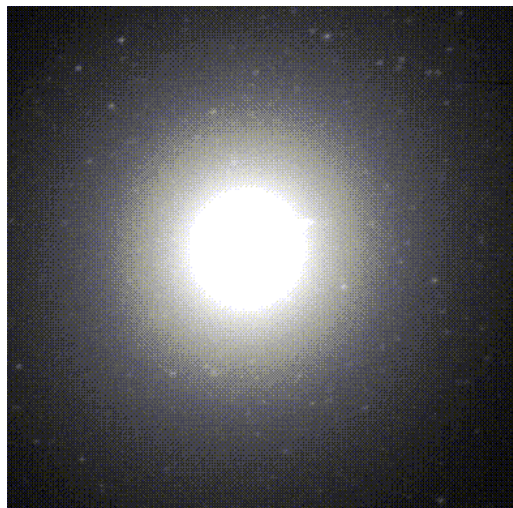


Figure 3.6: M87 – an example of an Elliptical Galaxy. (Credit: Anglo-Australian Telescope, David Malin).

Perhaps a relevant piece of information is the observational fact that in some galaxies ordinary matter is distributed roughly spherically rather than in a disk. Such galaxies are called elliptical galaxies and one such example is shown in **Figure 3.6**. This immediately suggests that mirror matter could, in principle, also form a spherical distribution. So maybe our galaxy and other similar galaxies have their ordinary matter embedded into an approximately spherical mirror galaxy. But observations tell us that every spiral galaxy similar to our galaxy always seems to have an invisible approximately spherical halo. Why should it *always* occur? The fact that it always seems to occur suggests that it probably cannot be explained just from some *random* initial conditions, such as angular momentum. I feel that the answer might lie in the initial chemical make up of the Universe, as I will explain in a moment.

Galaxies are believed to be formed from a giant collection of particles held together by gravity. In other words, they were once a huge gas cloud. Within these huge systems, particles are continually

colliding off each other. These collisions do two things. They create a pressure which can resist the force of gravity. If this is all that they did, the gas would never collapse; it would just sit there. However, the pressure can be reduced over time if the collisions are able to excite the atoms/molecules into higher energy levels. The excited atoms subsequently radiate photons (which eventually escape from the gas) and the atoms move back to their lowest energy state. In this way heat can be removed from the gas allowing it to become more tightly compressed, that is, to collapse.

Importantly, the collapse process occurs quite independently for the ordinary matter and mirror matter components. Why? Because collisions are an electromagnetic process, which acts independently on ordinary and mirror matter: Ordinary particles can collide with ordinary particles, mirror particles can collide with mirror particles, but ordinary and mirror particles cannot collide with each other. This means that the temperature and pressure profiles of the ordinary and mirror matter components are, in general, completely different and evolve differently. The dynamics of such a self gravitating two-component collapsing huge gas cloud is very complicated. Complicated enough perhaps to explain the vast array of galaxies and structures that are seen in the Universe.

One thing that is known though is that the way in which such a thing evolves depends quite sensitively on its initial chemical composition. Chemical composition refers to the proportions of the different elements and molecules that are present. The initial chemical composition of the ordinary matter could be quite different from the initial chemical composition of the mirror matter. Why? The answer may end up being due to the initial conditions at the very instant when the Universe was created – during the ‘big bang’ – and I will say a few more words about this later on. This means that the evolution of the ordinary and mirror matter components could be quite different. One could easily imagine that the rate of collapse of mirror matter into compact systems such as mirror stars/planets is much faster than ordinary matter which reduces the ‘friction’ between the mirror matter components in the galaxy thereby preventing collapse of the mirror matter into a galactic disk. In other words, mirror stars and planets might condense out of the primordial galactic soup

before the mirror matter has time to collapse onto a disk.

It therefore seems possible for a roughly spherical halo predominately made of mirror matter to exist. It would contain mirror stars, dust and maybe also large gas clouds... But how can we test this idea?

Waiting for an exploding mirror star...

There are several ways of testing this idea that our galaxy is full of mirror matter objects such as mirror stars. First, old massive stars do not just fade away; they collapse with a bang in a titanic explosion called a supernova. These explosions are so powerful that they may even outshine the galaxy in which they appear. Such events though are quite rare, occurring in our galaxy about once every few hundred years or so. One of the most spectacular took place on the 4th of July in 1054.

Chinese observations at the time recorded that the star was so bright that it was even visible during the day-time, and was nearly as bright as the Moon at night-time. Curiously, strange lights in the sky are also reported every year in the United States also on the 4th of July, but the origin of these more recent events is undoubtedly of terrestrial origin.... The remnants of the 1054 supernova explosion, known as the Crab nebula, still exists (**Figure 3.7**) and is one of my favourite astronomical pictures. [My most favourite astronomical picture is, of course, Vincent Van Gogh's *Starry night*].

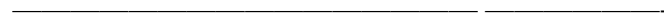
The last recorded supernova event in our galaxy occurred in 1604. So we should be overdue for another... In fact in 1987 a supernova in a nearby galaxy exploded and was visible with the naked eye as well as in underground experiments, as I will explain in a moment.

How does a star get into trouble? Stars evolve peacefully for millions of years, however nothing lasts forever (including diamonds!) and eventually the star runs out of nuclear fuel. When this happens the core of the star collapses under its own weight in less than a second. If the star's mass is less than about eight solar masses then the end product is a white dwarf – an object about the size of the Earth with a mass of about the Sun. However, if the star's

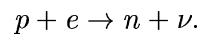
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Figure 3.7 here



mass exceeds about 8 solar masses then the end product of this gigantic explosion is something even weirder. When such a heavy star collapses, the pressure becomes so great that all of the electrons are pressed into the protons which combine to form neutrons and neutrinos,



This is a weak interaction process, which only becomes energetically possible because of the huge gravitational pressure. Anyway,

the neutrinos escape leaving behind a tightly compressed ball of neutrons – called a ‘neutron star’. An object heavier than our sun, but with a radius of only about 15 kilometres. One spoonful of this material would weigh more than New York City... Clearly such material should be handled with care. If swallowed seek medical advice...

In the case of the 1987 supernova explosion, not only was the large increase in brightness observed, but the burst of neutrinos was detected in underground laboratories in Japan and the USA. A total of 20 neutrino events over a time scale of just 12 seconds were recorded. As I will discuss in later chapters, neutrinos are expected to be a window into the mirror world. A tiny mixing force is allowed and would have the effect of changing half of the supernova neutrinos into mirror neutrinos. Unfortunately, because of various large uncertainties, the initial number of supernova neutrinos that would be expected to arrive at the Earth cannot be precisely determined, so we can’t tell whether half of the neutrinos are missing. This unsatisfactory situation may improve in the future with the great advances in neutrino detectors that now exist.

Even more interesting, though, is the implications of the conversion of mirror neutrinos into ordinary neutrinos which would happen if a *mirror star* explodes. This could make a mirror supernova effectively ‘visible’ even if no visible light is emitted. It would be a phantom explosion detectable only with neutrinos *. (Actually another possibility, which I will discuss in chapter 5, is that a tiny force allowing for photon mirror photon transitions could make mirror stellar explosions produce an observable burst of photons as well as a neutrino burst).

Although there is as yet no evidence of such phantom stellar explosions this is not unexpected since we know that nearby ordinary supernova explosions are relatively rare events. The estimated rate

*It is possible that an ordinary supernova explosion could mimic an exploding mirror star if the light from the ordinary supernova were blocked out by interstellar dust. However, even this possibility can be tested by looking at the direction of the neutrinos. The direction of the neutrinos from an exploding ordinary supernova should come from within the disk of our galaxy (if it happens to be one of the few halo ordinary stars it certainly won’t be obscured by dust). On the other hand, the neutrinos from an exploding mirror star will most likely come from the halo, that is, in a direction out of the plane of the galactic disk.

of ordinary supernova explosions is roughly once every few hundred years – so it may not be surprising if the rate of mirror supernova explosions also turns out to be low.

Discovery of mirror stars?

On quite a different tack, even invisible stars can reveal their presence through their gravitational effects on light. In 1986, Bohdan Paczynski had a good idea¹³. His idea was to mount a search for dark matter based on the idea that a massive object could act as a sort of lens. Even if we can't see the massive object, its gravity can bend the light coming from a more distant star around it, in much the same way that light gets bent as it passes through a magnifying glass. If there are invisible bodies floating in the halo of our galaxy it is possible that they should pass between us and our line of sight to a background star. If this happens then the gravity magnifies the light from the background star as the light passes around the invisible object – causing the background star to brighten. This effect is illustrated in **Figure 3.8**.

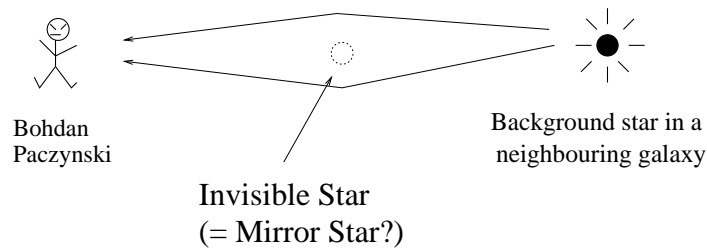


Figure 3.8: Magnification of a star's light by the gravity of an invisible 'star' (Mirror star?). The light bends around the invisible star just like light bends in a magnifying glass.

Because the invisible star, the background star, and our solar system, are all in relative motion, the magnification can only last for a finite time. The more massive the invisible object (the lens), the stronger its gravitational effect and the longer the period of increased brightness. For masses in the range from planet size to several times the Sun's mass, the brightness lasts from a few hours to as much as a year or so. However, even if the halo of our galaxy was full of invisible massive objects, the chance that one of these objects would pass between us and a particular background star is very low. In fact, it can be estimated that the chance is about one in a million, but the odds can be improved by simultaneously monitoring a large number of stars over several years.

Four teams of researchers began the search nearly a decade ago. First off the blocks was the French collaboration *Experience de Recherche d'Objets Sombres (EROS)*, which was closely followed by the *Optical Gravitational Lensing Experiment (OGLE)*, run by Paczynski and colleagues at the University of Warsaw in Poland, the large Australian - US *Massive Compact Halo Objects (MACHO)* project, and a smaller French effort called *Disk Unseen objects (DUO)*. All four use ground based telescopes and a large amount of computer memory to store the brightness measurements of millions of stars. When these projects started it was expected that the most likely candidate for the invisible halo objects were low mass stars called brown dwarfs weighing less than 10% the mass of the Sun. Such lightweights would be too faint to see and thus might be the invisible component of our galaxy. However, what they found was not lightweights but stellar-weight objects, with a typical mass of about half the mass of the Sun, and enough events to account for nearly half the estimated mass of the halo. Several such events are shown on the following page in **Figure 3.9** obtained by the MACHO experiment¹⁴.

Thus, instead of finding what they most expected, the observations were able to exclude lightweight objects from being a significant component of the halo. More interesting though, is that the results can be viewed as evidence for mirror matter, since mirror stars should have a typical mass similar to that of ordinary stars – which is close to about half the mass of the Sun. In other words,

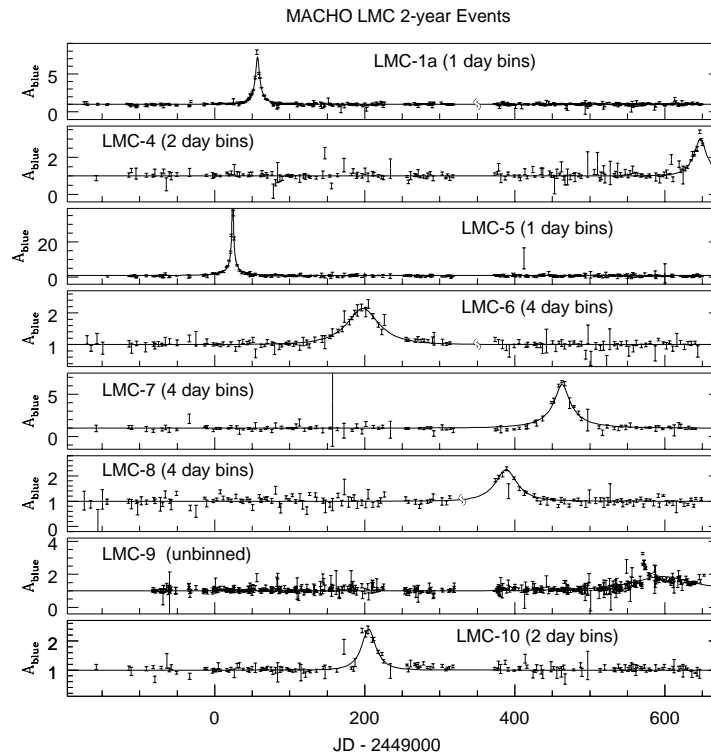


Figure 3.9: Eight distinct ‘MACHO events’. The figures show the intensity of light from a background star (vertical axis) as a function of time. The light from the background star gets amplified for a certain duration, which occurs because an invisible star passes in front of the background star. In each of these cases the background star is in the Large Magellanic Cloud (LMC) – a nearby galaxy.

the data is roughly consistent with what you could expect with a mirror matter halo. The MACHOs are just mirror stars, or perhaps mirror white dwarfs... Put another way, MACHOs are really Massive Astrophysical Compact Halo *Mirror* Objects (MACHMOs).

Even more remarkable is the inferred total mass of the MACHOs found in the experiments. The outcome is that the MACHOs make up only half or a bit less of the inferred mass of the halo¹⁵. Recall

our earlier discussion – the mass of the halo could be inferred from the motion of stars at various distances from the centre of the galaxy. The fact that the results from the MACHO experiments falls short in accounting for all of the mass of the halo suggests that there must be another component to the halo which does not show up in the MACHO experiments. Actually this feature can also be plausibly explained by the mirror matter theory. Mirror stars don't make up the entire halo simply because mirror matter, like ordinary matter, exists in two forms: In the form of mirror stars which are the MACHO events obtained in the experiments, as well as in the form of mirror dust and gas which do not leave any observable signal. [These particular experiments were only sensitive to *compact* systems such as star-sized objects, while the gravitational effect of clouds of gas and dust would be too dispersed to have been observed].

While plausibly explaining the results of these experiments is one thing – rigorous proof is another. Obviously it is difficult to rigorously prove that the MACHOs 'observed' in the experiments are mirror stars (unless one of them happens to explode in our galaxy, leading to an observable burst of neutrinos). On the other hand, if we take the mirror matter theory seriously, MACHOs are predicted to exist, and if they really are the dark matter then the results of the MACHO experiments really had to find a positive result for MACHOs about half the mass of the Sun. The fact that the results from the MACHO experiments are consistent with this prediction is strong evidence for the theory. Still, if it was the only evidence for mirror matter, then the case for its existence would be far from compelling. In short, it would be nothing to write home about – let alone a book! However, I will identify seven major puzzles in astronomy and particle physics, each plausibly suggesting that mirror matter exists.

MACHOs or WIMPs?

Let us finish this chapter with a brief discussion of the main alternative model for the dark matter. While mirror matter can lead to the formation of mirror stars, which are an example of a Massive Astrophysical Compact Halo Object (MACHO), the main alterna-

tive candidate for the invisible dark matter is appropriately called WIMPs. WIMPs are hypothetical Weakly Interacting Massive Particles. Their invisibility arises because it is assumed that they don't couple to photons. In fact, they interact only by extremely weak short-range interactions and consequently they seldom collide with each other (or with ordinary matter) which means that they can't collapse to form star sized objects. They cannot therefore explain the MACHO events. Actually they appear to have great difficulty in explaining many of the specific observations on the nature of dark matter. For example, WIMP dark matter makes specific predictions for the density profile of dark matter in galaxies which seems to be in strong disagreement with observations¹⁶. Furthermore, WIMPs seem unable to explain the inferred complexity of dark matter. Of course it is possible that I may be biased! In defence of WIMP theories one can say that they are very popular among particle physicists.

In view of their popularity, many experimenters have been searching for WIMPs for a long time. The idea is that these weakly interacting particles could make an observable signal in purpose-built underground detectors. Instead of going into the boring technical details, let me say something about the flavour of the WIMP search. Even better, let me quote one of the WIMP enthusiasts themselves. Twelve years ago (1989), L. Krauss eloquently captured the excitement of the hunt when he wrote in colourful language¹⁷:

You are a graduate student in physics. It's late Saturday night and you would much rather be at a party. Instead, you are a mile underground, in a cavernous enclosure, entertained only by the sound of a cooling fan whirring in the desk-top minicomputer that is monitoring pulses received from the gargantuan device located in the main chamber next door. It has been a boring eight-hour shift and you long to take the elevator ride up the mine shaft to the surface, to breath the fresh air and to watch the night sky, the stars twinkling, and the cool, evanescent glow of the moon bathing the earth's surface. You are, after all, studying to be an astrophysicist, not a geologist. When you forsook a lucrative programming job in order to return to graduate school, you envisioned working at a huge radio telescope aimed at the heavens, sensing the faint pulses

emitted by quasars billions of light-years away. Yet here you are, deep underground, monitoring a new experiment built by a collaboration among four universities located on three continents. In order to pass the time you watch the calibration pulses appear with clocklike regularity on your monitor, noting how each exactly reproduces the last.

Suddenly, almost too fast to sense, you notice something momentarily different about the signal. You halt the on-line output on the computer and call up the program that single-steps through the data. While the program loads on the machine, your mind races. There is a small chance that the pulse you saw, or imagined, is the infinitesimally small signal from an elementary particle making up a totally new type of matter never before observed on earth that interacted in your detector. If so, this could be the first time this particle has interacted in the ten to fifteen billion years since it was created in the fiery Big Bang. You may be looking at a signal from the beginning of time! Such particles may constitute one hundred times more material, by weight, than everything we can see put together, thereby governing the structure, evolution, and eventual fate of the universe! Your discovery could affect the way we think about the universe as dramatically as had Copernicus's assertion that the earth moves about the sun...

Or perhaps it is just a bit of noise in the detector...

This was published in 1989, and unluckily for that poor graduate student, it was in fact a 'bit of noise in the detector'; he's still down that mine shaft waiting for a signal from the dawn of time. He's long given up hope of any excitement and regrets not taking that lucrative programming job...

Despite more than a decade of dedicated searches, no WIMPs have been detected. While I suspect that WIMPs do not exist, I definitely support such experiments – so long as I don't have to do them! It's the only way of knowing for sure. Experiments are the essence of science...

Beauty and the Beast

The most popular manifestation of WIMPs comes from a particle physics theory called ‘supersymmetry’. Supersymmetry is one of those good ideas which does not seem to be used in nature. Supersymmetry is a symmetry which connects each of the known types of elementary particle with a hypothetical ‘super partner’ of a different spin. That such a symmetry can exist is quite non-trivial. For the mathematically minded supersymmetry holds much charm. However, its implementation as a symmetry of particle interactions is very troublesome for experiments. Most important is that the supposed ‘superpartners’ of each of the known elementary particles must have the same mass as the ordinary particles. This feature is very similar to the properties of mirror particles or anti-particles; they also have the same mass as their corresponding ordinary particles. That’s what the symmetry tells us. The problem with supersymmetry is that if they did have the same mass, then the superparticles would have been experimentally discovered many years ago in laboratory experiments. There is simply no known way of making them invisible in the Lab – except by breaking the symmetry. It is very sad. Supersymmetry is probably what Thomas Huxley had in mind when he wrote, ‘The great tragedy of science: the slaying of a beautiful hypothesis by an ugly fact’, or maybe not.

Although it is possible to write down theories with hypothetical superparticles which have ‘broken symmetry’, they tend to be very complicated because there are essentially unlimited ways of breaking the symmetry. The resulting construction is called the ‘minimal supersymmetric standard model’, which has more than 100 free parameters – and that’s the minimal model! Nevertheless, supersymmetry is very popular among particle physicists because they can write lots of papers predicting all of the experimental effects that these 100 parameters allow. Anyway, because of all these parameters it is possible to arrange things so that the lightest supersymmetric particle is neutral and stable, and can therefore be the dark matter of the Universe. It seems to me though, that this scenario is not very compelling because it is *ad hoc*. For example, there is no theoretical reason for any of the supersymmetric

particles to be stable once the symmetry is broken. Overall, it has always seemed to me that supersymmetric models are very ugly, principally because they are so complicated and arbitrary.

This is in sharp contrast to the manifest beauty of mirror symmetry which can be completely unbroken if mirror matter exists. The microscopic properties of the mirror particles are then completely fixed without any problems for existing experiments. One could also imagine breaking mirror symmetry by giving the mirror particles heavier or lighter masses – but this leads to seven years of bad luck! I should know, I toyed with such a model in 1994, exactly seven years ago. Of course, beauty is not necessarily the same as truth. Beauty always involves some subjective judgement. In the end we must each follow our own judgement, the truth of the (mirror) matter will be decided by careful experiments and observations.

* * *

If mirror matter does indeed exist in our galaxy, then binary systems consisting of ordinary and mirror matter should also exist. Although systems containing approximately equal amounts of ordinary and mirror matter are unlikely due to, for example, the differing rates of collapse for ordinary and mirror matter (leading to a local segregation of ordinary and mirror matter), systems containing predominately ordinary matter with a small amount of mirror matter and vice versa, should exist. Interestingly, there is remarkable evidence for the existence of such systems coming from extrasolar planet astronomy, the subject of the next chapter.