Welcome to the Museum of Dark Matter

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"One way of looking at things is ..."

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Figure 1.1. The Museum of Dark Matter

Welcome to the Museum of Dark Matter

1 Introduction

1.1 We are creatures living on a small planet in a vast Universe. We could have been extremely unlucky by possessing a dull biology, by living on a dull planet, and by existing in a dull Universe. We could have been boring, unintelligent, and stupid.

1.2 Instead we are extremely lucky to possess a large brain, to live on an exciting planet, and to exist in an amazing Universe. We are, in fact, intelligent, clever, and inventive. There is a lot of really interesting stuff all around us and we are well on our way to understanding some of it.

1.3 With that I bid you welcome to the Museum of Dark Matter. I hope you enjoy your visit and that you will come away knowing a few things that you did not know before.

1.4 Figure 1.1 is a picture of the Museum of Dark Matter. Of course there's nothing there. And that's the whole point of this book. There is no dark matter. Dark matter does not exist.

1.5 For the past 50 years (and longer) scientists (mainly astronomers) have been engaged on a wild goose chase, a futile quest, to find this mystical substance known as dark matter. But there is no dark matter, there really is nothing there, and the hypothesis of dark matter is destined to follow other theories that people thought were "a good idea at the time", such as phlogiston (the element for fire) and the luminiferous aether (the medium for light).

1.6 I am no doubt arrogant and heretical for proclaiming that dark matter does not exist, and the gods may well punish me for my hubris. I also know I am not allowed to dismiss the existence of dark matter without being prepared to put something else in its place. So I have an alternative to dark matter and I think it is a much better idea. That is what this book is all about; it is the exposition of an alternative to dark matter. This alternative is a really simple idea I came up with way back in 2015. This will be a new idea to everyone and I spend some time in explaining what this idea is and why it is really simple.

1.7 I have written this book in a somewhat non-standard way. I have not written it as a normal book with blocks of continuous text grouped into chapters. Instead I've written it as numbered paragraphs grouped together into topics, much in the way of the Koran or the King James' Bible. To me this is the natural way to present the material and it also makes referencing individual paragraphs really easy. I have also tried to put in a reasonable number of illustrations; simply because pictures are usually a much clearer way of getting an idea across.

1.8 I normally shy away from being dogmatic and so I should retrench a little from what I stated in paragraph 1.5. I do not like to say this idea is wrong and this other idea is right. My approach is generally to take the line that "one way of looking at things is ..."

1.9 For example: if we are drawing a map of Paris we may do so using "one way of drawing a map of Paris is to assume that the Earth is flat ..." This works perfectly well for an area the size of Paris even though we know the Earth is round and our assumption of a flat Earth is wrong. So throughout this book my approach is generally that of "one way of explaining these observations without using dark matter is ..."

1.10 This book is aimed at the non-technical reader and so it contains only a limited number of equations. A few technical items are laid out in chapter "30: Technical". But for the hardened technician, who wants the full physics and mathematics, there are a series of PDF files that can be downloaded from: **www.varensca.com**

1.11 Some of you may find this book a little annoying with the level of explanation. Some things are explained in detail whereas others are not explained at all as I assume a moderate level of knowledge. You are all clever readers so I trust that, where my explanations are lacking, you will find what you need at your local library, by asking a friend, or by searching the Internet.

1.12 And for the reader who thinks this book might be just another crackpot theory (which, of course, it might be) I suggest you read chapters "2: Eureka"; "11: The Conjecture"; "17. How It Works"; "18: Galaxy Rotation Curves". And then think again. (Note: I have given this book a score of "-5" on the John Baez Crackpot Index.)

1.13 So onwards into the Museum. There are many rooms to visit and many artefacts to marvel at. And, just like a museum, you don't have to follow a prescribed path; you are free to wander wherever your fancy takes you. So go on; have some fun.

2

Eureka!

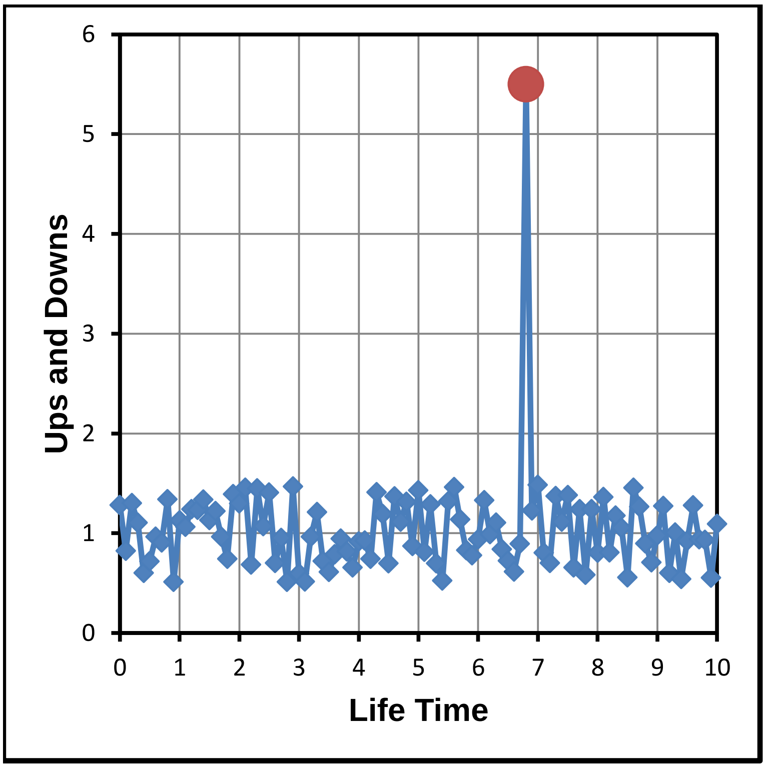

Figure 2.1. "Eureka!" moment. Life is full of ups and downs. Just occasionally you may have a "Eureka!" moment.

Have you ever had a Eureka moment?

1 Eureka!

1.1 Have you ever had a "Eureka!" moment?

1.2 Life is full of ups and downs. On many occasions things go wrong: you fail an exam; a friend dies; you don't get the job you wanted. On many other occasions things go right: you get to University; you buy your first house; you marry your sweetheart.

1.3 But perhaps once or twice in your lifetime, or perhaps never, you come up with something that, from your point of view, is truly astonishing. This is illustrated in Figure 2.1 above, where the blue line represents life's ups and downs, and the large red dot is a "Eureka!" moment.

1.4 My "Eureka!" moment took place on Saturday 25th July 2015 when I suddenly arrived at a solution to a previously unsolved problem; a problem that had troubled the world of science for over half a century.

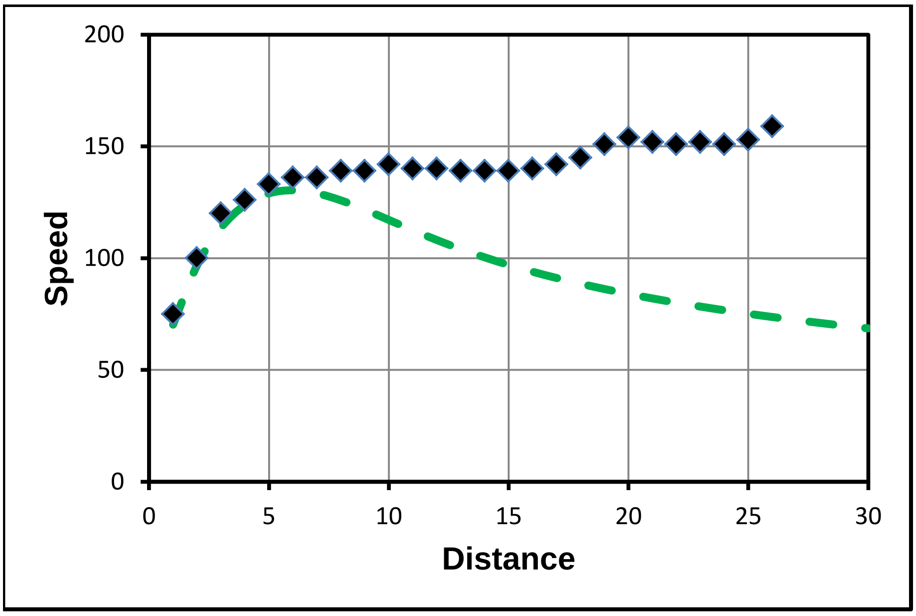

Figure 2.2. A galaxy rotation curve. The black diamonds are the observed values of the rotation speed. The dashed green line is the theoretical curve for Newtonian gravity.

1.5 The unsolved problem was the rotation curves of spiral galaxies. The rotation speed was expected to decrease with distance from the galaxy centre in agreement with Newton's law of gravity. However, the observations showed no such decrease; in fact almost every spiral galaxy showed a flat rotation curve and in some cases the speed even increased.

1.6 An example of the problem is shown in Figure 2.2. The black diamonds are the observations and the dashed green line the expected curve for Newtonian gravity. Beyond a distance of 5 units the rotation speed was expected to drop off. But the galaxy was not obeying the rules, the rotation speed showed no sign of a decrease and continued outwards with a slight increase.

1.7 There were only two possible solutions to this problem. Either (a) Newton's law of gravity was wrong and had to be changed, or (b) an enormous amount of extra matter had to be added to the outer regions of the galaxy. Nobody (or rather very few scientists) wanted to change Newton's law of gravity, so option (b) was adopted and scientists postulated the existence of a vast halo of invisible material enveloping the whole galaxy. And thus "dark matter" was born.

1.8 In Figure 2.2 (above) the discrepancy in the speed at distance 25 is about a factor of two. Newtonian gravity predicts a speed of around 75, but what is observed is a speed of around 150. This may not seem a huge discrepancy but, when you do the calculations, the amount of dark matter that has to be added is around five times the observed mass of the galaxy.

1.9 I had never liked the idea of dark matter; to me it felt intuitively wrong. I had looked at this problem on and off for many years without coming up with any serious alternative to dark matter. But then, in July 2015, I suddenly came up with a new concept, a third option, a theoretical idea where I could do the calculations and compare my results with the observations.

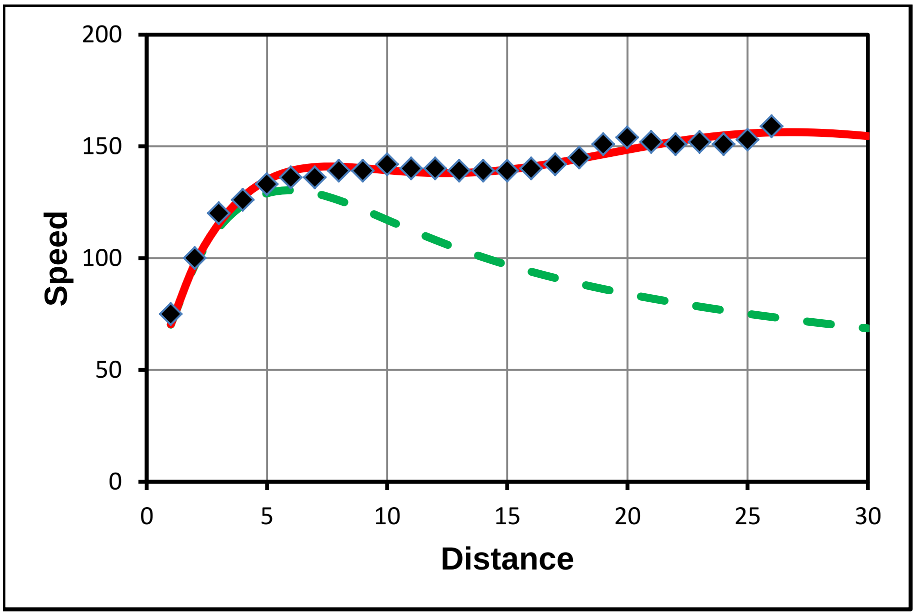

Figure 2.3. A galaxy rotation curve. This is the same galaxy as in Figure 2.2. The black diamonds are the observed values of the rotation speed. The dashed green line is the theoretical curve for Newtonian gravity. The solid red line is our new theoretical curve following the "Eureka!" moment.

1.10 There is a quote from physicist Richard Feynman about how we should proceed whenever we come up with a new idea:

> *"In general we look for a new law by the following process. First we guess it. Then we compute the consequences of the guess to see what would be implied if this law that we guessed is right. Then we compare the result of the computation to nature, with experiment or experience, compare it directly with observation, to see if it works. If it disagrees with experiment it is wrong."*

1.11 In July 2015 I was on leave from work. So I sat down for a few days at home, worked out the theory, and did the calculations for one galaxy. At that point there was no guarantee that my numbers would fit the data. My third option could go the way of countless defunct ideas that other scientists had come up with over the years. But finally I completed the calculations and plotted my results for the rotation curve against the observations. The result was Figure 2.3. An almost perfect fit. I had passed the Feynman test. "Eureka!"

1.12 Of course, you should never trust the results from one single case. So I repeated the calculations for a further five galaxies, and almost perfect fits were obtained in all five cases.

1.13 At this point I had a very simple idea that could explain the rotation curves of spiral galaxies without the need for any dark matter. You might think that should be enough but, of course, it is not. Dark matter is a concept that has worked its way into many areas of astronomy and cosmology and become firmly entrenched there. It has had all the advantages of being first; it has simply been put out there without having to disprove other options, because there weren't any there at the time. Now if you come along with an alternative idea you can't simply put it out there; instead you have to look at every place where dark matter is invoked and demonstrate why your alternative is not just as good but is in fact better.

1.14 This book looks at all the places where dark matter is used and shows how the third option can explain what dark matter explains. It also explains a few troublesome observations where dark matter hasn't been invoked. And it makes several predictions that can be tested against observations to show that the idea is correct and that dark matter does not exist.

1.15 The next section (chapters 3 to 10) explains dark matter and the astronomical situations where its existence is needed to explain the observations. We then introduce our new idea, what I have called "The Conjecture", and cover some background concepts that are needed (chapters 11 to 17). In chapters 18 to 24 we see how "The Conjecture" copes with all those places where dark matter provides the current explanation. Towards the end of the book we make some predictions that should allow our new idea to be tested (chapter 26), note some minor problems with the idea (chapter 27), and add some extras (chapters 28, 29).

3

The Dark Matter Hypothesis

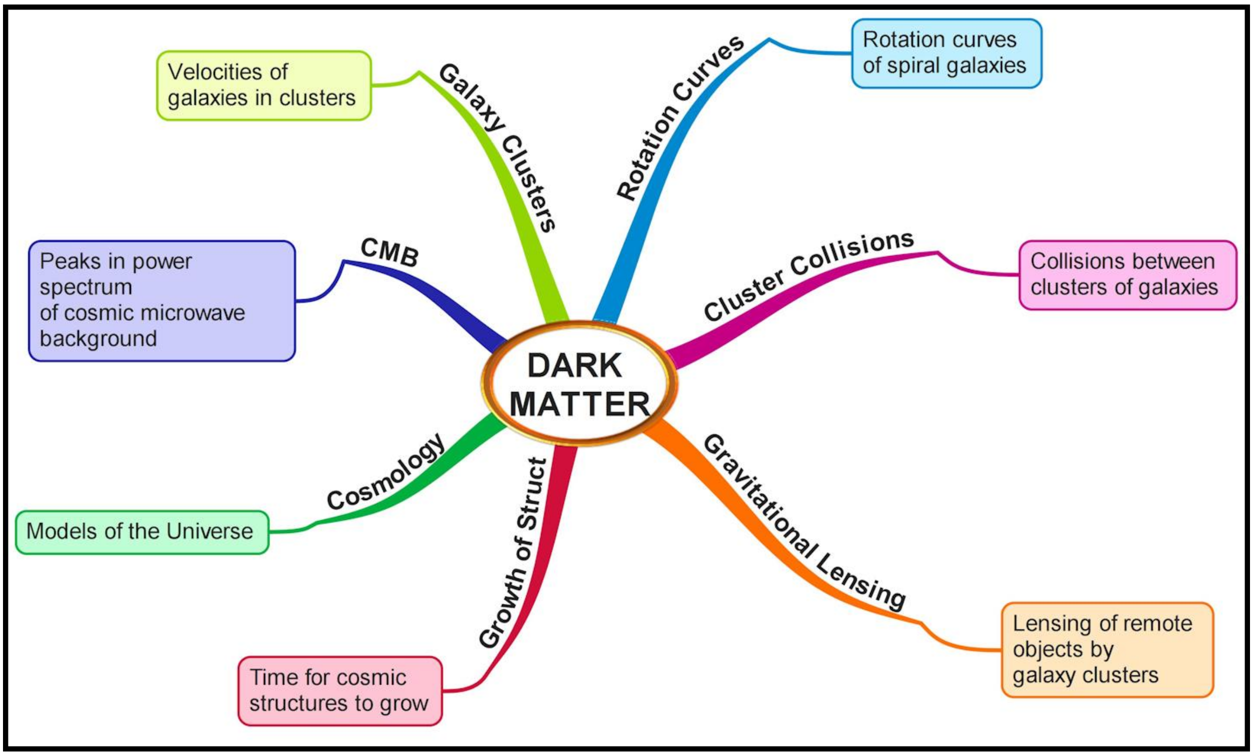

Figure 3.1: Mind map showing areas of astronomy where dark matter is needed.

We look at the idea of dark matter and list the observations that require its existence.

1 Dark Matter

1.1 We have a growing number of astronomical observations that we cannot explain in terms of normal matter and the law of gravity.

1.2 The clearest example is the rotation curves of spiral galaxies. Here the velocities of the stars in the spiral arms are way too high to the explained by the mass of the galaxy and the law of gravity. The mass needs to be greater by at least a factor of five. This is a huge discrepancy especially when we consider that discrepancies in physics are usually less than 1%, not a whopping 500%.

1.3 Gravity is always involved in these problem observations. It is always objects made of normal matter interacting with one another through gravity. The normal laws of motion and gravity should be sufficient to explain what is going on, but they don't. Something else is involved.

1.4 The simplest solution is to postulate the existence of additional matter that we can't see. Dark matter is the hypothetical form of matter that is assumed to be there in order to explain the rotation curves of spiral galaxies. It turns out that it can also help out with the other astronomical phenomena where the amount of normal matter observed is insufficient to explain what is going on.

1.5 The existence of dark matter was hinted at by Fritz Zwicky in 1933 from observations of the Coma cluster of galaxies. He found a discrepancy of a factor of over one hundred, but this was later reduced to around ten with better observations and better distance measurements. Dark matter was made more prominent in the 1960s and 1970s by Vera Rubin and others using observations of the rotation curves of spiral galaxies. Today dark matter is a major concern and there are numerous research teams attempting to track it down.

1.6 So far there has been no direct detection of any dark matter particle. However, it is not unusual for physical particles to be proposed a long time before they are detected. The neutrino was proposed in 1930 but not detected until 1956. The Higgs boson was proposed in 1964 but not detected until 2012.

1.7 In astronomy the vast majority of physical processes that are observed do not need dark matter at all. Dark matter is not needed for: the physics of stars; stellar evolution; binary stars; planetary systems; the physics of nebulae; the workings of the Sun and the solar system; and so on.

1.8 On the Earth dark matter is not required to explain any phenomena. Dark matter is not needed for: geography; geology; atmospheric physics; the workings of the oceans; plate tectonics; and so on. All the Earth sciences have worked well up to now without invoking dark matter, and they continue to work well without it.

1.9 In the major branches of physics there is no requirement for dark matter. Dark matter is not needed for: statics; dynamics; electricity; magnetism; optics; fluid mechanics; thermodynamics, and so on.

1.10 In the Standard Model of particle physics dark matter is not needed. The 12 fermions together with the bosons are all that are required to explain the whole of atomic and nuclear physics, and by extension the whole of chemistry. Quantum mechanics does not need dark matter and none of the modern theories of particle physics has ever suggested or warranted the existence of dark matter. No particle physics experiments have ever detected anything that might look like a dark matter particle.

1.11 So the whole of science has been working for the last few hundred years without the need for dark matter. And today just about the whole of science continues quite happily without it as well. In the whole of science the only place where dark matter is needed is in a handful of astronomical observations where gravity is involved.

2 Observational Scenarios

2.1 Dark matter is required to explain the nature of many astronomical observations. There is always a short-fall in the amount of matter involved, never a surplus. Observations only ever show the so-called "missing mass problem". No phenomenon has been observed where there is too much matter present.

2.2 We now look briefly at the different situations on an individual basis where the existence of dark matter is invoked. These are shown in Figure 3.1.

2.3 **1: Rotation Curves of Galaxies.**
The stars and gas in the outer regions of spiral galaxies are revolving about the galaxy centre with speeds that are too high to be produced by the observed matter. Around five times more dark matter than normal matter is needed.

2.4 **2: Speeds of Galaxies within Clusters of Galaxies.**
Within clusters of galaxies individual galaxy members have speeds that are far too high for the observed amount of matter. The clusters should have dispersed a long time ago. Five to ten times more dark matter than normal matter is needed to hold the clusters together.

2.5 **3: Gravitational Lensing**
The pictures of some clusters of galaxies show short arcs of light. These are the gravitationally lensed images of galaxies that are much further away. The mass required to produce these images is at least five times that of the matter observed in the clusters. This missing mass is presumed to be dark matter.

2.6 **4: Collisions between Clusters of Galaxies**
Occasionally clusters of galaxies collide with one another. The individual galaxies pass straight through but the gas in the clusters collides and gets left behind. Gravitational lensing shows that the dark matter, which must be present, also passes straight through without interacting with anything, including itself.

2.7 **5: Cosmic Microwave Background**
The power spectrum of the cosmic microwave background shows features that are thought to be caused by acoustic oscillations. The computer models that explain these features require dark matter to be present and have at least five times the energy density of normal matter.

2.8 **6: Cosmology**
The standard model for explaining the Universe from the end of inflation up to the present time is the ΛCDM model of cosmology (cosmological constant Λ + Cold Dark Matter).

This model also has to have around five times more dark matter as normal matter in order to explain the evolution and appearance of the Universe.

2.9 7: Growth of Structure

The density fluctuations at the time of the cosmic microwave background were around 1 part in 100,000. There is insufficient time for gravity working on its own to have pulled matter together and created the observed structures in the Universe; galaxies; clusters of galaxies. Dark matter would have started coalescing much earlier and provided the time for the observed structures to grow.

2.10 The seven cases listed above are more or less independent of one another. There could have been seven separate explanations, one for each case. The fact that one single agent, namely dark matter, provides an explanation for all of them, creates a formidable case in favour of dark matter. Any alternative hypothesis has to explain all the cases, not just one or two of them.

3 The Nature of Dark Matter

3.1 Modern theories of cosmology require dark matter, and another puzzling component "dark energy". Figure 3.2 shows the relative proportions of dark matter (27%), dark energy (68%), and normal matter (5%) that make up the total energy density of the Universe as it is now. At the time of the Cosmic Microwave Background (~380,000 years after the Big Bang) dark energy was essentially absent and the proportions were approximately dark matter (83%) and normal matter (17%).

3.2 Normal matter covers everything that exists on the Earth, in the Sun, and in the stars. It includes all the particles that make up the Standard Model of physics: quarks; protons; neutrons; neutrinos; electrons; photons; etc. We, humans, are made of normal matter. Normal matter interacts with light and we can observe astronomical objects because they emit, reflect; or absorb light.

3.3 Dark matter, on the other hand, does not interact with light at all, so we cannot observe it directly. We can only observe it indirectly through its gravitational effect on other matter. Dark matter has not been identified with any a specific particle, and the ways it interacts with itself and normal matter are still unknown. This makes it difficult to design experiments that can attempt to observe it directly.

3.4 Normal matter is often referred to as "baryonic matter", i.e. made of baryons. "Baryon" refers to just those subatomic particles that are made of three quarks, such as the proton and the neutron. However, in the astronomical context "baryonic" is used to apply to all subatomic particles including the electron and neutrino. As normal matter is described as baryonic, dark matter is conversely described as "non-baryonic".

3.5 Many ideas have been put forward as to what dark matter might be made of. Dark matter can be labelled as either "hot" or "cold" depending on how fast it moves.

3.6 "Hot dark matter" is particles that move close to the speed of light. So this covers the known types of neutrinos. It turns out that the masses of these neutrinos are too low for them to be dark matter. But other, much heavier, neutrinos have been suggested; these would lie beyond the standard model.

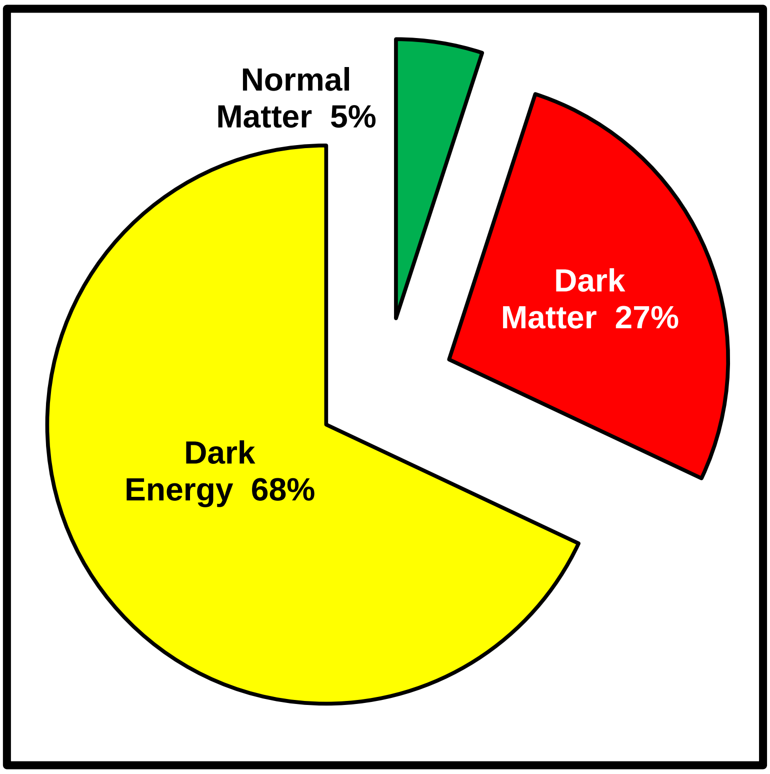

Figure 3.2: Current make-up of the Universe in terms of energy density. Dark Matter accounts for about 27%; Dark Energy about 68%; Normal Matter about 5%.

3.7 "Cold dark matter" is matter that moves much slower than the speed of light. Many candidate objects have been proposed including planets, faint brown dwarf stars, and black holes. And several new particles have also been proposed such as axions and WIMPs. Axions have been proposed separately to solve a problem in particle physics known as the "strong CP problem", which involves difficulties arising from some interactions involving charge (C) and parity (P).

3.8 WIMP is the acronym from Weakly Interacting Massive Particle. Weakly Interacting means the particles only interact with normal matter through the weak nuclear force. Massive implies the speed of the particles is only a fraction of the speed of light, as any particle travelling at the speed of light has to have zero mass. WIMPs are thought (guessed) to have masses similar to or greater than those of the proton or neutron. WIMPs are hypothetical so the way they interact with normal matter is unknown. Nevertheless there are many experiments going on around the world attempting to detect them.

3.9 The model that best explains the evolution of the Universe is the ΛCDM model (cosmological constant Λ + Cold Dark Matter). WIMPs are the best candidate for the particle of cold dark matter. As such they must interact with one another weakly and clump together gravitationally. These interactions must lead to large objects, such as the halos surrounding galaxies and clusters of galaxies, but not lead to smaller or more condensed objects, such as stars.

4 Newton and Einstein

4.1 In this book we are interested in how things move in an astronomical context for which we have two theories of mechanics: (a) Newton's laws of motion, and (b) Einstein's special theory of relativity. We are also concerned with gravity for which again we have two theories: (a) Newton's law of gravity, and (b) Einstein's general theory of relativity.

4.2 Newton's laws of motion are an approximation to Einstein's special theory of relativity. The speed of light is 300,000 km/s and differences between the theories only become important when the speeds are greater than around 10% the speed of light. At low speeds Einstein's theory reduces to Newton's. This is fortunate because Newton's laws are much simpler to work with and make our tasks somewhat easier.

4.3 Observations of the rotation curves of spiral galaxies show that the stars in the outer region are moving with speeds up to 300 km/s. That is 0.1% the speed of light; so we are definitely in the low speed regime where Newton's laws of motion are perfectly adequate. In clusters of galaxies the highest velocities of galaxies are below 1000 km/s, so at most 0.3% the speed of light. So again Newton is perfectly adequate.

4.4 Einstein's general theory of relativity explains gravity as arising from the curvature of space-time. Its effects become significant only when the curvature is large, i.e. when we are close to large masses such as the event horizon of a black hole. At great distances from large masses general relativity reduces to Newton's law of gravity. This is the situation for everything covered in this book and Newtonian gravitation is sufficient for everything we need to look at. So throughout the book we refer to Newtonian gravitation rather than general relativity. (We will see there is an exception where Einstein's general relativity is needed for gravitational lensing.)

4.5 In summary Einstein's special and general theories of relativity are the theories we should be using for mechanics and gravity. However, we are in the low speed and weak field regimes where Newton's laws are perfectly adequate.

5 Summary

5.1 There are a growing number of astronomical situations involving gravity where normal matter is not following the normal laws of physics. Our knowledge is clearly incomplete and we must either change our ideas on how gravity works or change our ideas on how matter behaves.

5.2 The generally accepted solution to the problem is to make the ad hoc postulate that large amounts of non-baryonic matter exist. This has been given the name "dark matter" and it must be at least five times more abundant then normal matter..

5.3 Dark matter is very successful in providing a single explanation for all the situations illustrated in Figure 3.1. Its existence is also widely accepted by the scientific community at large.

5.4 To date no dark matter particle has ever been detected in any physical experiment.

4

Galaxy Rotation Curves

Figure 4.1. Spiral galaxy NGC 1566. (Credit: ESA/Hubble & NASA)

We look at the problem with stars moving around the centres of spiral galaxies and ask the question "what is the problem and how does dark matter solve it?"

1 Introduction

1.1 Figure 4.1 shows spiral galaxy NGC 1566 as seen by the Hubble Space Telescope. It is around 12 Mpc away; some 15 times further than the Andromeda Galaxy. We are seeing the galaxy face on. The spiral arms are very obvious and they show that the galaxy is rotating. NGC 1566 is rotating clockwise so the spiral arms are trailing and over time we would expect them to wind up. The central nucleus is also obvious; this is where most of the mass is concentrated. If we could see NGC 1566 from the side then it would appear as a thin disk with a spherical bulge at its centre.

1.2 For objects like NGC 1566 we can measure the radial velocity, that is the speed towards or away from us; around 1500 km/s for NGC 1566. For face on galaxies, like NGC 1566, we cannot tell how fast it is rotating. For spiral galaxies that are more edge on the radial velocity also gives us their rotation speed. If the speed is measured at different points across the disk we end up with the rotation curve for the galaxy.

1.3 As mentioned above, most of the mass of a spiral galaxy is concentrated in the central region. So we would expect the rotation speed in the outer regions to fall off in accordance with Newton's law of gravity, i.e. proportional to the inverse square root of the distance.

1.4 The equation for the rotation speed of a star at distance r from the galaxy centre is

$$v(r) = \sqrt{\frac{G\,M(r)}{r}} \tag{4.1}$$

where $v(r)$ is the speed; $M(r)$ is the mass inside r; G is the gravitational constant.

2 Observational Data

2.1 Figure 4.2 shows a different spiral galaxy, NGC 3198. It is a normal spiral galaxy, some 14 Mpc distant, and sufficiently inclined to our line of sight that we can measure its rotation speed. The galaxy has a central bulge where most of the mass is concentrated; there is relatively little mass in the spiral arms.

2.2 Figure 4.3 shows the observed rotation curve for NGC 3198. The blue diamonds are the observations; they show a steady rise from the galaxy centre to around 8 kpc, and then a near constant value of around 150 km/s all the way out to almost 40 kpc. The green dashed curve is the expected curve for Newtonian gravity, i.e. this is the curve given by equation (4.1).

2.3 The vast majority of spiral galaxies behave in a similar way to NGC 3198; NGC 3198 is in no way exceptional. However, it is difficult to observe the outer regions of many spiral galaxies as their arms become very faint; so the flat part of the rotation curve is not seen in all cases. This applies particularly to dwarf galaxies.

Figure 4.2. Spiral galaxy NGC 3198.
(Credit: John Vickery and Jim Matthes/Adam Block/NOAO/AURA/NSF)

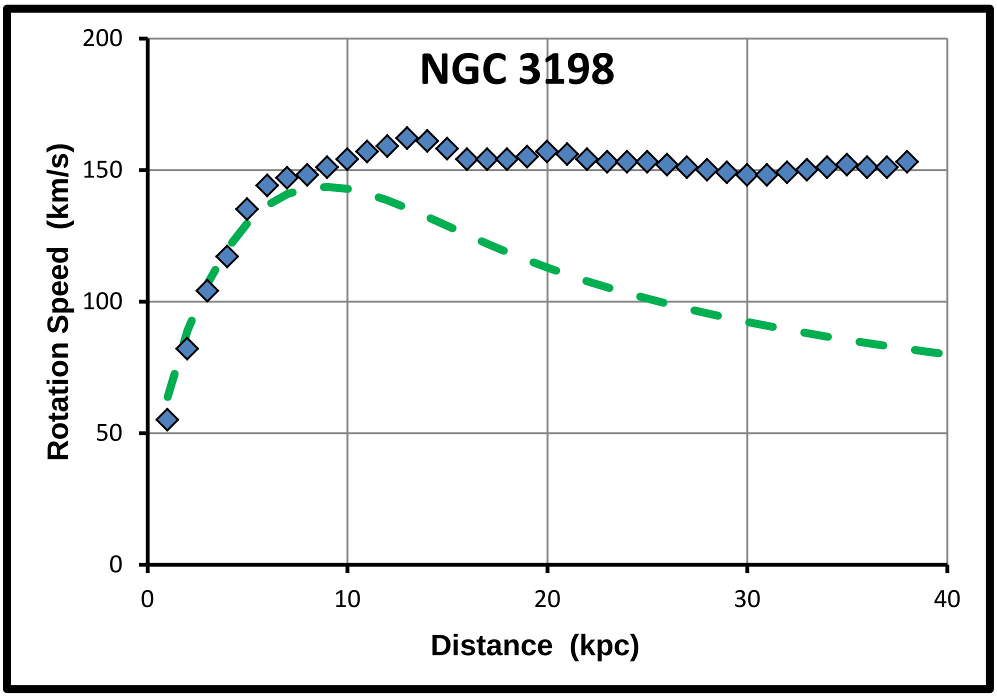

Figure 4.3. The observed rotation curve for galaxy NGC 3198. The blue diamonds are the observations; the green dashed curve is the expected curve for Newtonian gravity.

2.4 Not all spiral galaxies show a flat rotation curve. In some galaxies the curve continues a gentle rise, and in others there is a turnover followed by a gentle decline. But in all cases there is a discrepancy between the observed rotation curve and that expected for Newtonian gravity.

3 Chain of Reasoning

3.1 NGC 3198 is a spiral galaxy with a large central mass that is surrounded by a rotating disk of stars.

3.2 NGC 3198 can be modelled as a central mass orbited by a disk of massless stars. The speeds are low compared to the speed of light and the gravitational force is small. These mean Einstein's special and general theories of relativity are not needed; Newton's laws are perfectly adequate.

3.3 The stars should obey Newton's law of gravitation and in the rotation curve the speed should show a drop off inversely proportional to the square root of the distance, as set out in equation (4.1).

4 The Problem

4.1 Figure 4.3 is the rotation curve for NGC 3198. The blue diamonds are the observed velocities. The green dashed curve is the expected rotation curve for Newtonian gravity, assuming a Gaussian density distribution for the normal matter. There is a clear disagreement between observations and theory, and this discrepancy gets worse the further we go away from the galaxy centre. This problem is present to some degree in all spiral galaxies.

4.2 The problem is that spiral galaxies are made of normal matter and the stars in the spiral arms should follow the normal laws of physics, but they don't. In many experiments the results are not obvious to the naked eye and have to be dragged out of the observations using complex algorithms and advanced statistics. Not so with galaxy rotation curves. We can simply look at the rotation curves of galaxies and the discrepancies jump out at us.

4.3 The conclusion has to be that either (a) there is more mass present than just the normal matter, or (b) that there is something wrong with our understanding of the law of gravity.

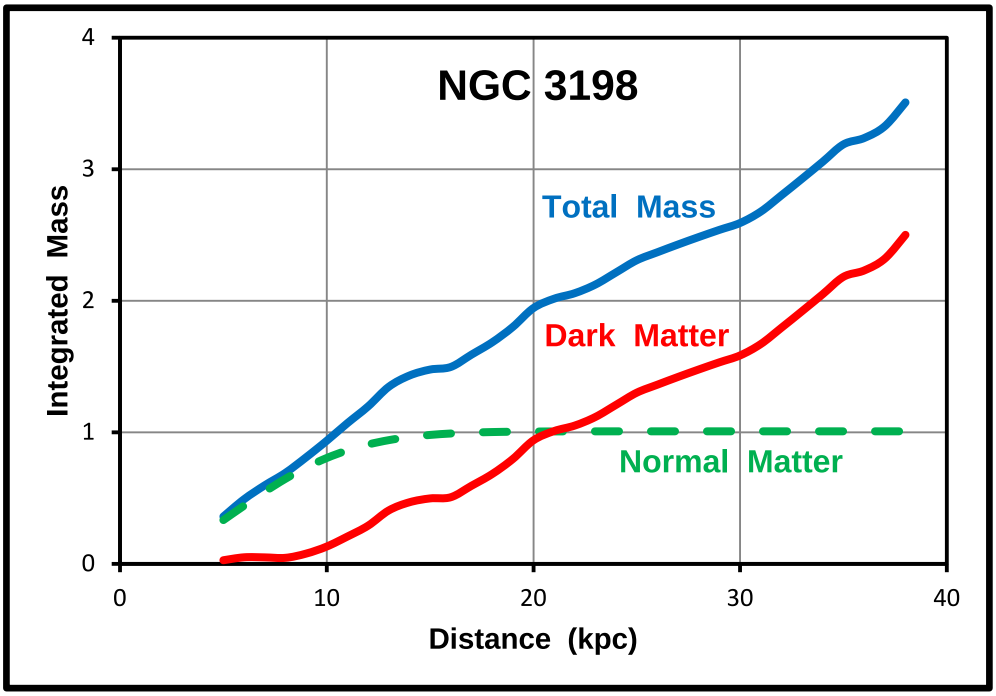

Figure 4.4. Graph of the amount of mass in NGC 3198 out to a certain distance. The graph is normalised so that the total mass of the normal matter is 1.0. It shows that out to 38 pc there is 2.5 times as much dark matter as normal matter.

5 The Dark Matter Solution

5.1 Dark Matter proposes the existence of a non-baryonic form of matter, dark matter. Every spiral galaxy lies at the centre of a large halo of dark matter that completely surrounds the galaxy. The additional mass provided by the dark matter halo is then sufficient to provide the extra gravitational force needed to account for the observed rotational velocities. There must be around five times as much dark matter as normal baryonic matter.

5.2 The rotation velocity depends on the square root of the mass, as is clear from equation (4.1). So we can see that adding more mass to the galaxy makes the rotation speed go up. This is exactly what dark matter does for us.

5.3 Figure 4.4 illustrates how the dark matter halo solves the problem of the rotation curve for NGC 3198. The green dashed curve shows the total amount of normal matter that is needed to generate the dashed green curve of Figure 4.3. The solid blue curve shows the total amount of matter required to generate the blue diamond observations of Figure 4.3. The solid red curve is the difference between the blue and green curves. It is attributed to the existence of dark matter.

5.4 Figure 4.4 is normalised so that the total mass of NGC 3198 is 1.0. The dashed green curve shows how the total mass of the galaxy increases as we move out from the centre and reaches 100% by 20 kpc, indicating there is little normal matter beyond this distance. However, the blue curve is still increasing at 20 kpc, and shows no sign of levelling off even at 38 kpc. This means the mass of the dark matter halo is still increasing at 38 kpc.

5.5 From Figure 4.4 we can say that, at 38 kpc, the amount of dark matter is at least 2.5 times the mass of the normal matter. It is generally accepted that the dark matter halo extends to much greater distances from the galaxy centre and that the total amount of dark matter is closer to 5.0 times the mass of the normal matter.

6 Summary

6.1 In spiral galaxies the stars in the spiral arms have speeds that are far greater than can be explained by the observed amounts of normal matter.

6.2 Either additional matter must be present or the law of gravity must be changed.

6.3 The addition of around five times more mass in the form of a large halo of dark matter solves the problem in a satisfactory manner.

5

Clusters of Galaxies

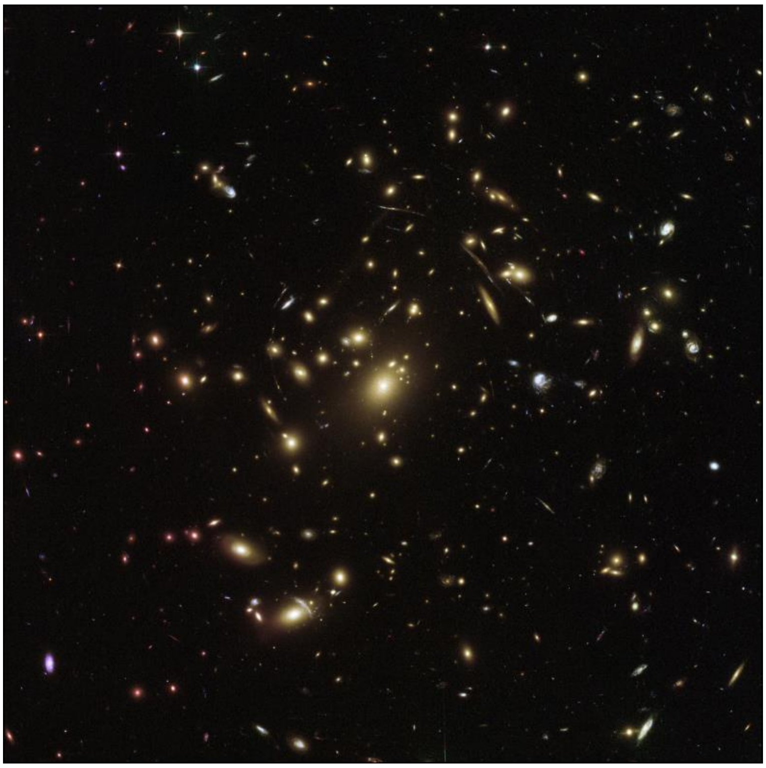

Figure 5.1. Cluster of Galaxies Abell 2537. Every object in the picture is a galaxy. The faint arcs are the gravitationally lensed images of more remote galaxies.
(Credit: ESA/Hubble & NASA)

We look at clusters of galaxies and answer the question "how does dark matter solve the problem of the high velocities of galaxy members?"

Figure 5.2. Globular Cluster M5. (Credit: ESA/Hubble & NASA)

1 Introduction

1.1 Figure 5.2 is not a cluster of galaxies. It is globular cluster NGC 5904 (better known as Messier 5 or M5), which orbits the Milky Way at a distance of around 7 kpc. There are over 100,000 stars in M5 and the Hubble image shows the central concentration of the stars with the numbers decreasing towards the outer edges. The stars in M5 are well over 10 billion years old, perhaps as much as 13 billion years old.

1.2 The age of M5 indicates that it must be an extremely stable system. The stars have neither dispersed into interstellar space nor collapsed into a single massive object. The stars have random orbits around the centre of the globular cluster and these orbits are stable with the orbital velocity of the stars balancing the gravitational pull of the cluster.

1.3 From the physics viewpoint M5 is a "relaxed" system and so should obey the virial theorem. The virial theorem states that the gravitational potential energy is twice the kinetic energy. We can estimate the total number of stars in M5 by measuring the amount of overall light emitted and knowing how much light a typical star gives out. We then know the distribution of mass and can get at the gravitational potential energy. Separately we can measure the velocities of the stars and get at the total kinetic energy. For M5 the theory works well and the gravitational potential energy is in good agreement with twice the kinetic energy. This also means there is essentially no dark matter in M5, or rather there is no need to invoke the existence of dark matter in M5 to explain how it has managed to exist for so long.

1.4 Figure 5.1 is a cluster of galaxies. It is the Hubble image of Abell 2537, which lies at a distance of around 1 billion parsecs (roughly 1000 times further away than the Andromeda galaxy). Just about all the objects in the image are individual galaxies. Similar patches of sky contain a only few galaxies so it is unusual to have so many all together in one place.

1.5 Abell 2537 contains thousands of galaxies and so is not immediately comparable to M5 with its hundreds of thousands of stars. Nevertheless Abell 2537 is a large concentration of galaxies in one place, and it appears to be old and stable. So we can carry out a similar analysis to M5 and ask whether or not the gravitational potential energy is twice the kinetic energy.

2 Observational Data

2.1 Images such as Figure 5.1 give the brightness & position for the galaxies. The centre of the cluster can be determined and hence the distribution of the galaxies with respect to the centre. So the overall geometry is known.

2.2 Spectroscopic observations of individual galaxies give their radial velocities. The average velocity determines the speed of the cluster as a whole. This average speed is subtracted from the individual speeds to give the relative speed of each galaxy with respect to the cluster centre.

2.3 Separately, clusters of galaxies contain a large amount of intra-galactic dust. The gravitational pull of the cluster heat the gas, which then emits X-rays. The X-ray brightness leads to an estimate for the mass of the gas.

2.4 Separately, many clusters of galaxies show the gravitationally lensed images of more remote galaxies. These observations give an independent estimate of the total gravitational mass of the cluster. This is discussed later in chapter "6: Gravitational Lensing".

3 Chain of Reasoning

3.1 Abell 2537 appears to be a stable cluster of galaxies grouped together in one place. The system can be considered to be "relaxed" and so must follow the virial theorem that the potential energy is twice the kinetic energy.

3.2 The radial velocity of the cluster as a whole is the red-shift and this determines the distance to the cluster from the Hubble law. This distance then fixes the geometry and determines the distances of individual galaxies from the cluster centre.

3.3 The mass of individual galaxies can be estimated from their brightness and the known mass-to-brightness ratio. The position of a galaxy within the cluster together with its mass gives the gravitational potential energy for that galaxy. The total potential of the cluster is then given by summing the individual potential energies.

3.4 The red-shift of individual galaxies gives their speed relative to the cluster centre. This speed and the mass define the galaxy's kinetic energy. The total kinetic energy of the cluster is found by summing the individual kinetic energies.

3.5 As mentioned above, the X-ray observations of hot intra-galactic dust and the gravitationally lensed images of remote galaxies both give rise to independent measures of the total mass of the cluster. All three mass measurements are in reasonable agreement with one another.

3.6 We now have both the potential energy and the kinetic energy, and we can check whether the virial theorem holds.

4 The Problem

4.1 Observations of clusters of galaxies show that the kinetic energy is around five times larger than the potential energy. The virial theorem predicts the kinetic energy should be just half the potential energy. The galaxies in the cluster are moving far too fast to remain bound to the cluster and the cluster should have dispersed well over a billion years ago. The shortfall in the amount of matter is about a factor of ten.

4.2 It is known that there is gas lying between the galaxies, intragalactic gas, and this has a mass similar to that of the galaxies. This reduces the discrepancy from a factor of ten down to a factor of around five

4.3 The discrepancy indicates that something else must be at work within the cluster holding the galaxies together. This something must be either a change in the way gravity works or a large amount of additional matter.

5 The Dark Matter Solution

5.1 The dark matter solution to the high speeds of galaxies within a cluster is that the cluster contains a vast amount of dark matter. The more mass the cluster has then the stronger the gravitational force and the faster the galaxies move. There must be around five times as much dark matter in the cluster as normal matter (galaxies and gas).

5.2 If we put in around five times as much dark matter as normal matter then this solves the problem. The dark matter is added as a massive halo that encompasses the whole cluster of galaxies. The dark matter fills the cluster with a density distribution that peaks at the cluster centre. This extra mass provides both the gravitational force required to hold the cluster together and the gravitational acceleration to make the galaxies move faster.

5.3 There is no doubt that dark matter does solve the problem and the factor of between five and ten is similar to that required to fix the problem with galaxy rotation curves as discussed in chapter "5: Galaxy Rotation Curves".

6 Summary

6.1 When the virial theorem is applied to clusters of galaxies it is clear that the observed mass is too small by a factor of between five and ten to account for the high velocities of the individual galaxies.

6.2 The addition of at least five times the observed mass of the cluster in the form of dark matter solves the problem with the virial theorem.

6.3 The addition of the extra dark matter also brings agreement between mass estimates obtained from gravitational lensing and the X-ray emission of the hot gas.

6

Gravitational Lensing

Figure 6.1. Galaxy cluster SDSS J1038+4849 better known as the "smiley face". The circular arcs form part of an Einstein Ring which is the gravitational lensed image of a remote galaxy situated far behind the galaxy cluster. (Image credit: NASA & ESA)

We look at how gravity affects light and ask the question "how does gravitational lensing tell us there is a missing matter problem in galaxy clusters?"

1 Introduction

1.1 The general theory of relativity is Einstein's theory of gravity and it supersedes Newton's law of gravity. In many situations Newtonian gravity is perfectly adequate, such as planes flying around the Earth, planetary motions in the solar system, and the rotation curves of spiral galaxies. However, Einstein's theory has to be used when very large masses are involved and when dealing with the paths travelled by light rays.

1.2 General relativity shows that a light ray grazing the surface of the Sun is bent through an angle of 1.75 arc-seconds. If we observed a distant object then it would appear on the sky to be displaced away from the Sun by 1.75 arc-seconds. This effect has been confirmed by observations during total eclipses of the Sun.

1.3 Another situation is the bending of light by the mass of an entire cluster of galaxies. Figure 6.1 shows one such case of "gravitational lensing" where the light from a remote galaxy has been bent by a whole cluster of galaxies. The cluster acts as a lens and bends the light rays to form the partial arcs of the so-called "Einstein Ring".

1.4 The amount of bending depends on the mass of the object and the "impact parameter", the distance of closest approach of the light ray to the object. If we know the amount of bending and the geometry of the situation then we can invert the problem and derive the mass of the object.

2 Observational Data

2.1 Gravitational lensing has been observed in over 50 clusters of galaxies. Most of the observations are not large sections of Einstein rings as shown in Figure 6.1, but rather small dislocated arcs scattered across the outer regions of the clusters.

2.2 In many cases it is not easy to get at the geometry from the observations. This is because the path of light rays through the cluster is quite complex as it depends on the distribution of galaxies throughout the cluster and the individual galaxy masses. Often a series of computer models has to be constructed and compared with the observations to pin down the geometry.

2.3 Images of the cluster enable the brightness of individual galaxy members to be measured. We know the mass-to-light ratio for galaxies; i.e. how much light is emitted by a galaxy of a certain mass. These lead to an estimate of the total light output from the cluster and so to the total mass of the galaxies.

2.4 X-ray images of the cluster give the amount of light output by the hot gas in the cluster. This leads to an estimate of the total mass of the gas.

3 Chain of Reasoning

3.1 The red shifts for the remote lensed galaxy and the cluster of galaxies give us the distances to the objects through Hubble's law.

3.2 The angular positions on the sky of the remote galaxy and the cluster of galaxies give us the angle through which the light rays have been bent. Together with the distances we essentially have the complete geometry.

3.3 General relativity gives the formula for the bending of light by a massive object.

$$\boldsymbol{\theta} = \frac{\mathbf{4}\,\boldsymbol{G}\,\boldsymbol{M}}{\boldsymbol{R}\,\boldsymbol{c}^{\mathbf{2}}} \tag{6.1}$$

where $\boldsymbol{\theta}$ is the angle through which the light is bent; $\boldsymbol{M}$ the mass of the galaxy cluster; $\boldsymbol{R}$ the impact distance; $\boldsymbol{G}$ the gravitational constant; $\boldsymbol{c}$ the speed of light.

3.4 The angle depends linearly on the mass of the bending object (cluster of galaxies) and inversely on how close the light ray gets to the bending object (cluster of galaxies). The larger the mass or the smaller the distance of closest approach then the larger the angle of bending.

3.5 The formula from general relativity is simply inverted to give the mass of the cluster of galaxies.

$$\boldsymbol{M} = \frac{\boldsymbol{\theta}\,\boldsymbol{R}\,\boldsymbol{c}^{\mathbf{2}}}{\mathbf{4}\,\boldsymbol{G}} \tag{6.2}$$

4 The Problem

4.1 Observations of the galaxies and hot gas give us an estimate for the mass of the galaxy cluster $\boldsymbol{M}$.

4.2 Red shift measurements give us the distance of the cluster, which leads to a measurement of the impact parameter $\boldsymbol{R}$ and the bending angle $\boldsymbol{\theta}$.

4.3 The problem is the observed bending angle $\boldsymbol{\theta}$ is far greater than that expected from equation (6.1). The alternative way of looking at the data is that the mass of the galaxy cluster must be much greater than expected from equation (6.2). The shortfall in the mass is a factor between five and ten.

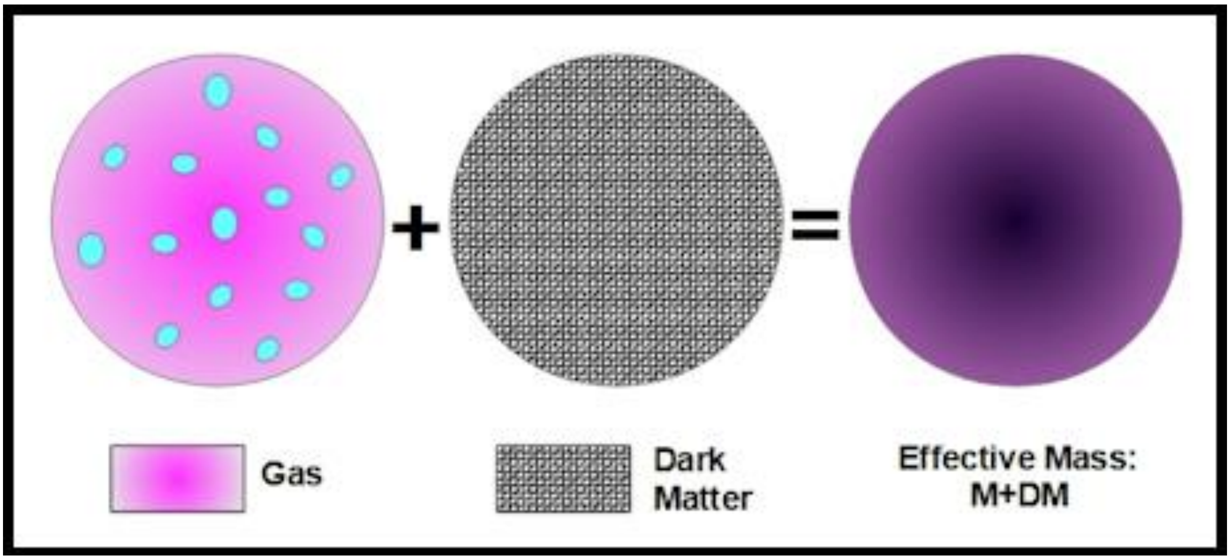

Figure 6.2. Schematic of how a cluster made of galaxies and gas, when given a large amount of dark matter results in an object with a substantially larger mass.

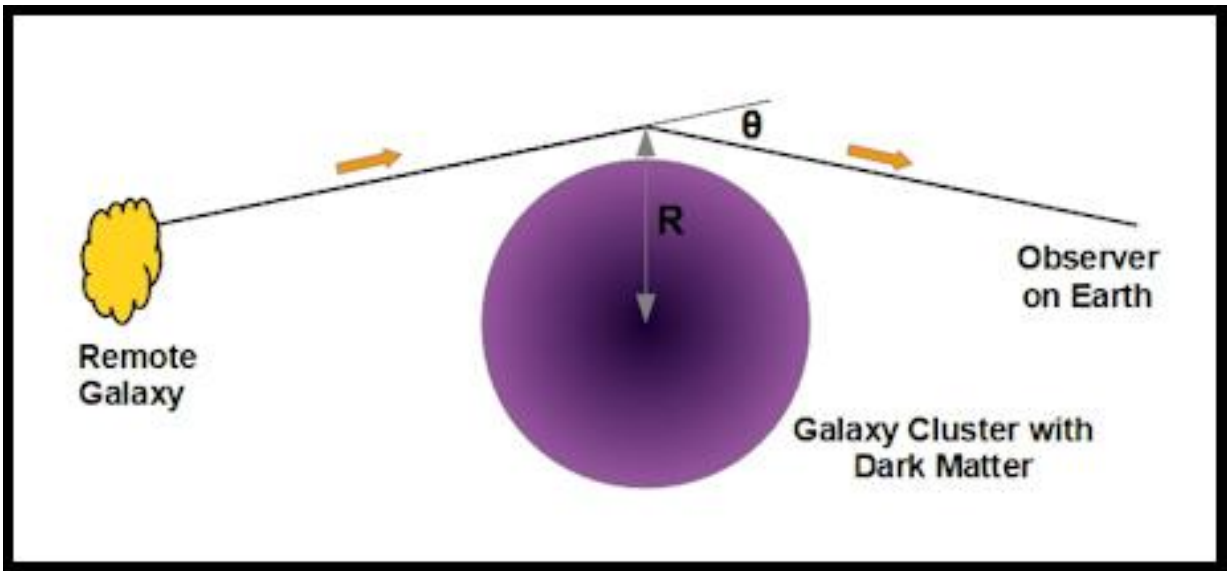

Figure 6.3. Schematic of the gravitational bending of light from a remote galaxy by a cluster of galaxies containing a substantial amount of dark matter.

5 The Dark Matter Solution

5.1 The observations of clusters of galaxies show there is not enough mass in the form of galaxies and hot gas to explain the gravitational lensing of remote galaxies. The dark matter solution is simply to add in enough dark matter to bring the total mass of the cluster up to that required for the gravitational lensing.

5.2 This is illustrated in Figure 6.2. The pink circle on the left represents the hot gas in the cluster and the blue ellipses are the galaxies. The black hatched circle in the middle represents the dark matter. The graded purple circle on the right represents the complete cluster of galaxies as the sum of the two components: matter (M); dark matter (DM).

5.3 Figure 6.3 illustrates how a light ray from a remote galaxy is bent by the cluster. The light ray can be thought of as approaching the cluster to within a distance, $\boldsymbol{R}$, at which point it is bent through an angle, $\boldsymbol{\theta}$. In this sense the cluster of galaxies acts as a simple lens. Of course, the bending does not happen at a single point; rather the path of the light ray is a continuous curve around the cluster.

5.4 The amount of X-ray emission of hot gas in the cluster gives the mass of the gas. A second estimate for the effective mass of the cluster is given by working out how much mass is required to support the gas in hydrostatic equilibrium. This mass estimate is in good agreement with the estimate from gravitational lensing; it also supports the existence of extra mass in the cluster.

5.5 So adding in five to ten times the observed mass of the cluster in the form of dark matter accounts for both the gravitational lensing and the hot X-ray emitting gas.

6 Summary

6.1 Many clusters of galaxies show arcs of light that are the gravitational lensed images of galaxies lying way beyond the cluster.

6.2 The mass of the galaxy cluster derived from the lensing is much greater than that derived from other observations. This means there is too little normal matter in the cluster to account for the gravitational lensing.

6.3 The addition of at least five times as much mass to the cluster in the form of dark matter reconciles all the observations with one another.

7

Collisions between Clusters of Galaxies

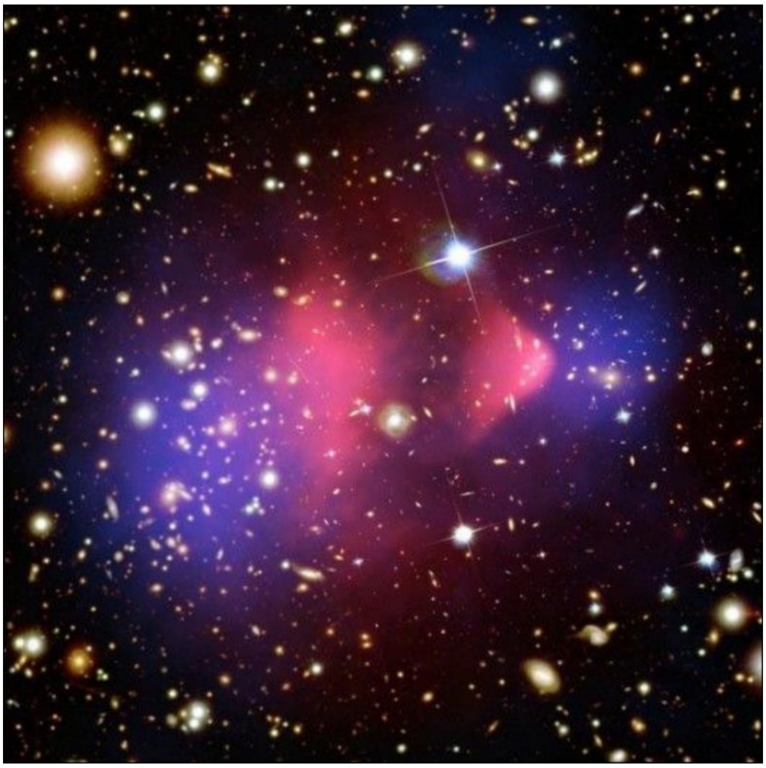

Figure 7.1. The Bullet Cluster: two galaxy clusters have collided and passed through one another. The main image shows the galaxy clusters. Superposed in blue is the mass inferred from weak gravitational lensing, and in red the X-ray emission from the hot gas.
(Image credits: Galaxies: NASA/STScI/Magellan/Univ Arizona/Clowe et al. Weak Lensing: NASA/STScI WFI/Magellan/Univ Arizona/Clowe et al. X-rays: NAZA/CXC/CfA/Markevitch et al.)

We look at collisions between clusters of galaxies and ask the question "in what way is dark matter involved in cluster collisions?"

1 Introduction

1.1 Clusters of galaxies are large groupings of galaxies in the same volume of space; they contain from hundreds to thousands of galaxies. An example is shown in Figure 5.1 in chapter 5 "Clusters of Galaxies". Clusters of galaxies were discussed in chapters "5: Clusters of Galaxies" and "6: Gravitational Lensing"; both chapters described the missing mass problems and how the addition of at least five times the mass of normal matter in the form of dark matter solves the problems. The dark matter increases the gravitation potential by a large amount sufficient to explain the high velocities of galaxy members and the gravitational lensing of remote objects.

1.2 Clusters of galaxies have their own peculiar motions within the Universe and collisions between clusters sometimes take place. During such collisions the galaxies simply pass through as they are relatively small compared to the size of the cluster and the chance of a galaxy-galaxy collision is tiny. The gas between the galaxies is not so lucky and the collision often results in the gas being stripped out and left behind as the clusters separate.

1.3 Weak gravitational lensing shows that the gravitating mass stays with the galaxies and not with the gas. This is interpreted as showing that the dark matter, like the galaxies, is not affected by the collision and simply passes straight through. The gas that is left behind usually has a mass greater than that of the galaxies and it might have been expected for the dark matter to remain tied to the gas.

2 Observational Data

2.1 Galaxy clusters are observed in many different ways including: direct images; X-ray images; weak gravitational lensing.

2.2 Images of galaxy clusters enable the individual cluster members to be identified leading to knowledge of the number of galaxies and an estimate of the total galaxy mass.

2.3 X-ray observations of the hot gas in the cluster give an estimate of the total mass of the gas. There is much more mass in the hot gas than in the galaxies and up to 90% of the normal matter can be in the gas.

2.4 Weak gravitational lensing gives an independent measure of the total gravitational mass of the entire cluster both normal matter and dark matter

2.5 Similar observations of pairs of galaxy clusters after they have collided and are now separating gives information on the effects of the collision. In most cases it is seen that the galaxies pass straight through, as does the dark matter. On the other hand the hot gas interacts directly and is observed to be left behind as the clusters separate.

2.6 Figure 7.1 shows an image of the Bullet Cluster where measurements of X-ray emission and weak gravitation lensing have been superimposed. The separation of the components is apparent. The gas, shown in pink, is left behind as the galaxies and dark matter, shown in blue, separate.

3 Chain of Reasoning

3.1 Clusters of galaxies not involved in collisions are observed (in X-rays) to contain a large amount of gas lying between the galaxies. The mass of the gas generally exceeds that of the galaxies by up to a factor of ten. Isolated galaxy clusters show that the galaxies, the X-ray gas, and the dark matter are all centred on the same location; there is no separation.

3.2 Clusters of galaxies that have been involved in collisions are observed (in X-rays) to contain little gas; instead the gas appears to have been stripped out by the collision and left behind between the separating clusters.

3.3 Weak gravitational lensing shows the mass of the separating clusters to be concentrated on the galaxies and not on the gas.

3.4 The conclusion is made that the dark matter in the clusters is not involved in the collisions and simply passes straight through. The dark matter in one cluster does not interact with the dark matter in the other cluster.

4 The Problem

4.1 Currently up to 90% of the gravitating mass of a galaxy cluster is thought to be dark matter. The remaining 10% is normal matter and up to 80% of this is the hot gas. So it is only 20% of normal matter, the galaxies, that stays with the dark matter and moves away after the collision. The bulk of the normal matter, the gas, separates from the dark matter and stays behind.

4.2 So 80% of the normal matter in galaxy clusters is in the gas. This gas is lost from the cluster during a collision. It is surprising that the dark matter, which has the majority of the gravitating mass, does not stay with the hot gas but sticks with the minority 20% of normal matter in the galaxies.

4.3 Other theories for galaxy clusters have problems in explaining what is going on in cluster collisions. Many of these theories modify the way gravity works and these have difficulties because most of the normal mass lies with the hot gas and not with the galaxies. After the collisions these theories would expect the gravitational lensing to be centred on the more massive gas component, rather than on the less massive galaxy component.

5 The Dark Matter Solution

5.1 The dark matter solution for collisions between clusters of galaxies is illustrated in Figures 7.2 & 7.3. The galaxies are shown as light blue ellipses; the hot gas filling the cluster in pink; the dark matter also filling the cluster in black hatching.

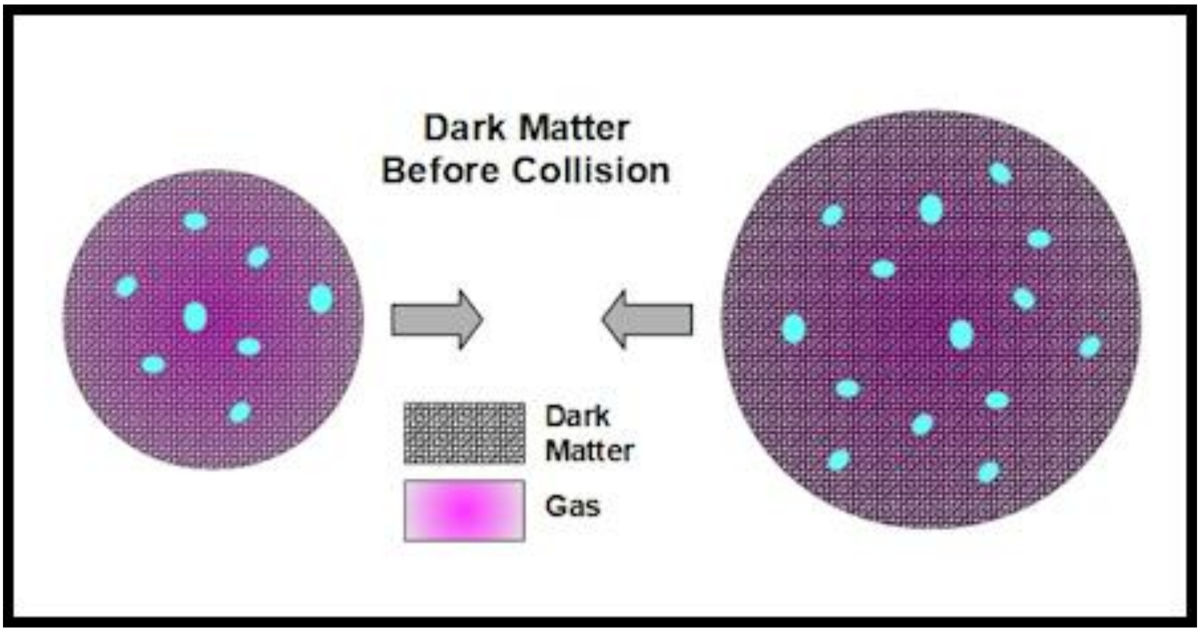

Figure 7.2. Two clusters of galaxies before collision. The galaxies (blue) are surrounded by hot gas (pink) and the whole embedded in dark matter (black hatching).

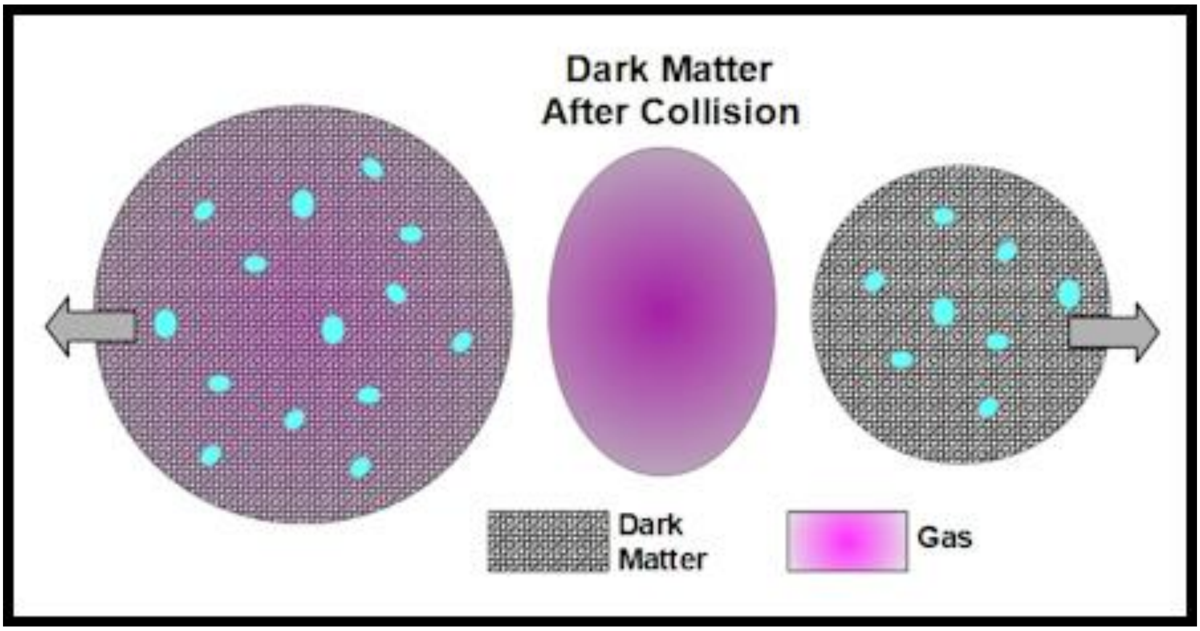

Figure 7.3. Two clusters of galaxies after collision. The galaxies (blue) remain embedded in dark matter (black hatching). The hot gas (pink) tends to get stripped out and left behind.

5.2 Before the collision each cluster is a stable relaxed system. The galaxies have their own velocities within the cluster but are trapped in its gravitational potential well. Their speeds are below the escape velocity for the cluster and they remain bound to it. The gas is also trapped in the cluster and its density increases towards the cluster centre. The gas is heated as it falls and is hot enough to emit X-rays.

5.3 During the collision the galaxies pass straight through. Within each cluster the separation between galaxies is large and the chance of any collisions is very low. The gas does interact strongly; the gas molecules collide with one another, exchange momentum, lose much of their translational velocity, and end up left behind.

5.4 The dark matter is also observed to pass straight through the collision and to stay with the galaxies. This shows that the dark matter hardly interacts with itself at all. If the dark matter particles were anything like gas molecules then something like gas pressure forces would be expected to come into play. Nothing like that occurs and the dark matter particles only interact with one another at the gravitational level.

5.5 After the collision the galaxies and the dark matter separate as they lose little of their momentum. The gas is stripped out and left behind.

5.6 The make-up of each cluster by mass is roughly 5% galaxies, 15% gas; 80% dark matter. After the collision the bulk of the mass remains in the clusters as each would have lost at most the 15% of the gas. The gravitational potential well formed by the dark matter is and should be sufficient to hold the cluster together. As the cluster continues on its way it will start to pull in a fresh supply of gas from the intergalactic medium and eventually replenish its content of hot X-ray emitting gas.

6 Summary

6.1 Clusters of galaxies are thought to be made of galaxies, gas, and dark matter. Most of the mass is in the dark matter, and the gas is more massive than the galaxies.

6.2 After two clusters have collided the gas, which has most on the baryonic mass, is often stripped out and left behind. The galaxies pass straight through as does the dark matter.

6.3 Some theories predict that the gas (most of the normal mass) should stay attached to the dark matter, but this is not what happens.

6.4 The dark matter does not appear to interact with itself, unlike gas molecules. Dark matter only interacts with itself and other objects gravitationally.

8

Cosmic Microwave Background

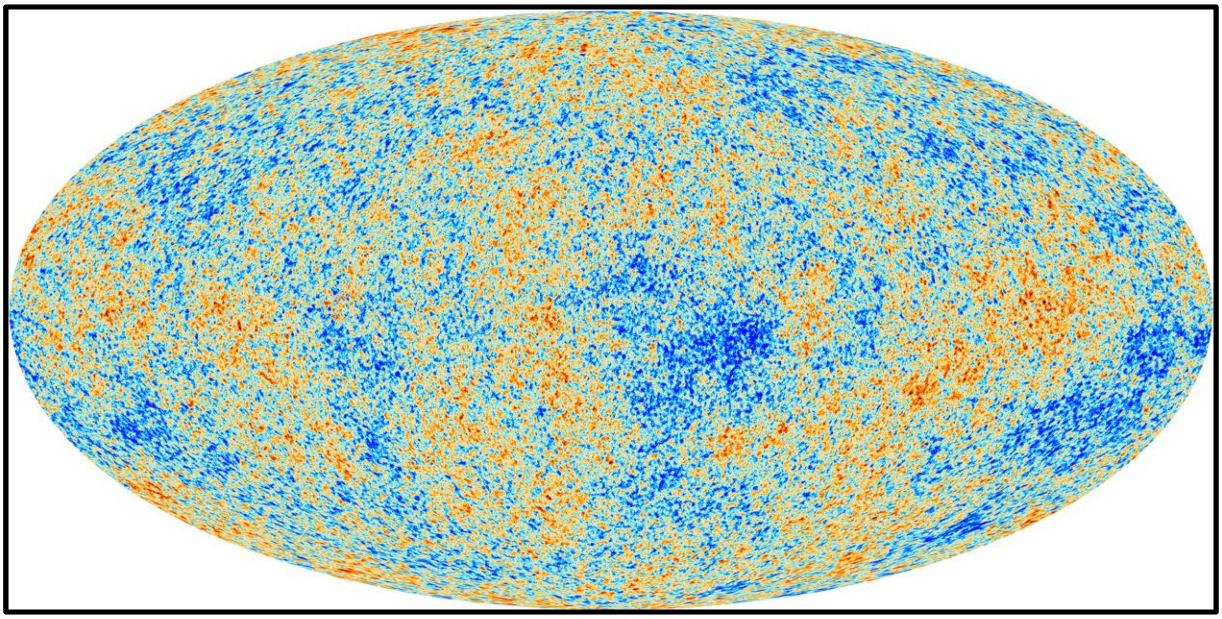

Figure 8.1. Whole sky map of the temperature fluctuations in the cosmic microwave background as observed by the Planck space mission. (Image credit: ESA)

We look at the cosmic microwave background and ask the question "what problems does the addition of dark matter solve?"

1 Introduction

1.1 The cosmic microwave background (CMB) is radiation that is reaching us now from a time when the Universe was just 380,000 years old and around 3,000 K hot. Before then normal matter was a hot plasma, essentially just charged particles (protons, electrons) and radiation. This was opaque to radiation; radiation could only travel a short distance before it was scattered by electrons. When the temperature dropped to around 3,000 K, the electrons and protons in the plasma started combining to form neutral hydrogen. With the electrons now locked up in hydrogen atoms the radiation was no longer blocked and could travel freely across the Universe. This is what we observe as the CMB.

1.2 Since the time of the CMB the Universe has expanded by a factor of 1100. This has stretched the wavelength of the radiation by the same 1100 and the 3000 K radiation is observed today in the microwave part of the spectrum with a temperature of just 2.73 K.

2 Observational Data

2.1 The CMB shows tiny fluctuations in temperature of around one part in 100,000. These fluctuations are shown in Figure 8.1, which is the all-sky map produced by ESA's Planck space mission. The original source of these fluctuations is thought to be quantum fluctuations from the time of inflation when the Universe was created.

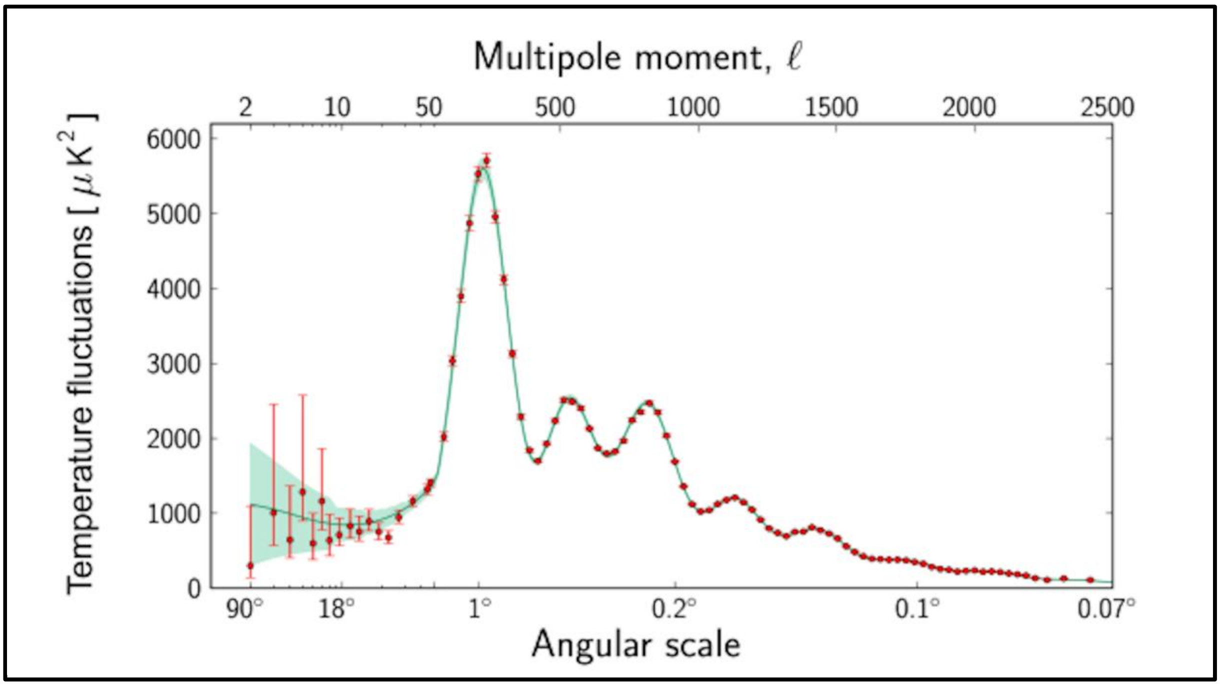

Figure 8.2. The correlation analysis (power spectrum) of the temperature fluctuations in the cosmic microwave background (CMB) as observed by the Planck space mission. (Image credit: ESA and the Planck Collaboration)

2.2 At the time of the CMB (around 380,000 years after the Big Bang) the Universe was a gas and as such could support sound waves; much in the same way that the gas in the Earth's atmosphere supports sound. These sound waves are referred to as "acoustic oscillations". They had preferred wavelengths that were determined by the distribution of matter (and dark matter) and the size of the Universe.

2.3 The power spectrum (correlation analysis) of the CMB show a series of peaks that are related to the preferred wavelengths and these are apparent in Figure 8.2.

3 Chain of Reasoning

3.1 The existence of the minute temperature fluctuations in the CMB and the peaks in the power spectrum were both predicted many years before the observations were made. So they give substantial support to the hypotheses that made the predictions.

3.2 Leading up to the time of the CMB, normal matter was a fully ionised plasma dominated by radiation and electron scattering. Density fluctuations could not grow under these conditions as any slight density enhancement was washed out by the dominant electron scattering.

3.3 It is presumed that dark matter does not interact with either normal matter or radiation, so density fluctuations in the dark matter could grow. By the time of the CMB the density fluctuations in the dark matter would have grown into substantial gravitational wells. Normal matter would then vibrate in these gravitational wells giving rise to the baryonic acoustic oscillations. These give rise to the peaks in the power spectrum of the CMB.

3.4 The interpretation of the peaks seen in the power spectrum of the CMB is neither immediate nor straightforward. The physics that goes into the interpretation comes partly from the ΛCDM (Lambda + Cold Dark Matter) model and partly from wave theory for the acoustic waves. The waves are the oscillations in the normal matter as it moves in and out of the dark matter gravitational potential wells.

3.5 Sophisticated computer models are required to carry out the complex calculations demanded by the physics. These models have a fair number of input parameters (between 10 and 50) including the relative amounts of radiation, normal matter, dark matter and dark energy. A large grid of models is computed and these are then compared with the observations to find the model that best fits the location and relative heights of the peaks.

3.6 The best fit model has, for the present composition of the Universe: 68% dark energy; 27% dark matter; and just 5% normal matter. This model is shown as the green line in Figure 8.2. The curvature of the Universe is another adjustable parameter and it turns out that the best fit model has a curvature close to zero implying the Universe is flat.

4 The Problem

4.1 The hypotheses and computer models do a really good job at explaining the observations of the CMB. There are no outstanding problems and so little incentive for scientists to look for alternative solutions.

4.2 A small worry is that any set of observations can be explained by any model provided the model has enough adjustable parameters. As mentioned above, the current models for the CMB have a fairly large number of adjustable parameters.

5 The Dark Matter Solution

5.1 The peaks in the CMB power spectrum are caused by acoustic waves in the normal matter. The gravitational attraction of regions of higher density pulls in the matter; the matter compresses and heats up; the pressure increases and eventually this overcomes gravity and forces the matter to bounce out again. This balance between gravity and pressure gives rise to the acoustic waves.

5.2 Dark matter does not play a direct role in the CMB. The CMB is radiation coming from the normal baryonic matter around 380,000 years after the Big Bang. Dark matter doesn't interact directly with normal matter and so it is not involved directly in the CMB radiation.

5.3 Dark matter is assumed to exist by the ΛCDM model (CDM=Cold Dark Matter) and its relative abundance is one of the free parameters input into the computer models that explain the CMB power spectrum.

5.4 The dark matter plays an indirect role in the CMB as it provides the gravitational potential wells needed to generate the acoustic waves in the normal matter. It is the temperature fluctuations of the matter in these waves that give rise to the peaks in the CMB power spectrum.

6 Summary

6.1 The power spectrum of the cosmic microwave background shows a number of peaks corresponding to different angular separations on the sky.

6.2 The role of dark matter is to provide the gravitational wells in which the normal matter can undergo the acoustic oscillations that give rise to the peaks in the power spectrum.

6.3 The ΛCDM model of the Universe is implemented as a large complex computer program. A large grid of calculations is carried out using this model and by varying the input parameters a good match can be found to the observed power spectrum.

6.4 The computer model with the best fit to the observations has 68% dark energy; 27% dark matter; and just 5% normal matter. The Universe is also flat with a zero curvature.

9

Physical Cosmology

Time	Event
10^{-32} s	Inflation
	Universe starts decelerating
10^{-6} s	protons & neutrons created
1,000 s	nucleosynthesis: hydrogen, deuterium, helium, lithium created
	dark matter clumps together
380,000 yr	cosmic microwave background
	normal matter clumps together
200 million yr	first stars
1 billion yr	first galaxies
10 billion yr	Universe starts accelerating
13.8 billion yr	Now

Table 9.1. Timeline for our Universe

We look as physical cosmology and ask the question "what cosmological problems are solved by the addition of dark matter?"

1 Introduction

1.1 "Cosmology" is the study of the Universe as a whole and is covered by several disciplines including religion and philosophy as well as by physics. "Physical Cosmology" is the scientific study of the Universe; an endeavour that involves making observations, developing theories, and constructing computer models. Physical cosmology examines the Universe on the large scale; so evolution; growth of structure; galaxy clusters; voids; galaxies; etc. It does not cover the details such as the formation of individual stars; these kinds of processes involve the complex interplay of many factors and are studied as separate subjects in their own right. So star formation and stellar evolution are essentially separate disciplines.

1.2 The most widely accepted theory for the Universe is the ΛCDM model, Lambda (cosmological constant) + Cold Dark Matter. This is a model where the energy density is made up of four components: radiation; normal matter; cold dark matter (CDM); and a cosmological constant (Λ). The cosmological constant, Λ, is usually associated with dark energy. The ΛCDM model also assumes that the motion of the Universe is governed by Einstein's theory of gravity, general relativity.

1.3 Physical cosmology assumes the Universe starts in the Big Bang with a period of exponential expansion known as "inflation", during which the Universe expands by at least 26 orders of magnitude. Inflation forces the Universe to be flat, i.e. the curvature of space-time, whatever it was before inflation, ends up as zero. Inflation ends by the time the Universe is only 10^{-32} seconds old. The ΛCDM model describes the Universe from this point onwards right up to the present day (and on into the future).

1.4 The key equation that governs the expansion of the Universe is the Friedmann equation, derived from Einstein's general relativity by Alexander Friedmann in 1922. For the flat Universe adopted by the ΛCDM model this is

$$\left(\frac{\dot{a}}{a}\right)^2 = H^2 = \frac{8\,\pi\,G}{3\,c^2}\,\varepsilon_c \tag{9.1}$$

where a is the length scale factor; $\dot{a}$ the rate of change of the scale factor; H the Hubble parameter; ε_c the critical energy density. We don't need to do any maths or physics with this equation, we just need to see that the square of the rate of expansion depends on the critical density.

1.5 The critical energy density, ε_c, is made up of the four components mentioned above

$$\varepsilon_c = \varepsilon_R + \{\varepsilon_B + \varepsilon_{DM}\} + \varepsilon_{DE} \tag{9.2}$$

where the different energy densities are: ε_R for radiation; ε_B for normal baryonic matter, ε_{DM} for dark matter; ε_{DE} for dark energy. The two terms within braces constitute the matter.

1.6 By definition a flat Universe means that the density is always the critical density, that is the density just large enough to slow down the Universe so that it eventually stops. So the sum of the four components shown in equation (9.2) above (radiation; normal matter; dark matter; dark energy) will add up to the critical energy density at all times during the Universe's history.

1.7 The energy density of dark energy, $\boldsymbol{\varepsilon_{DE}}$, is a fixed constant (the cosmological constant); it does not change with time. The other three components change with time in different ways, and at different times the four components can make different contributions. After inflation radiation was the largest term and dominated the others. For much of the subsequent history matter (normal matter plus dark matter) was dominant. And going into the future, radiation, normal matter, and dark matter will get smaller and smaller allowing dark energy to become the dominant component.

1.8 These changes happen because the different components scale in different ways as the Universe expands. The density of matter scales, as expected, with the volume; so if the linear size of the Universe doubles then the density decreases by a factor of eight (volume is length cubed). Note however that the total amount of matter in unchanged; it is the density that changes. For radiation the wavelength of light is also stretched so it decreases by another factor or 2 making a total decrease of a factor of 16.

1.9 On the other hand the density of dark energy is unchanged as it is constant and a property of space. So, unlike matter where the total remains constant, the total amount of dark energy increases by a factor or eight, as it is directly proportional to the total volume. This, as you no doubt have realised, breaks the law of the conservation of energy; but most scientists argue that it's OK in this case.

2 Observational Data / Chain of Reasoning / Problems

2.1 Big Bang

The Big Bang is a somewhat loose term. In this book we use it to mean the first five minutes of the Universe. This covers the initial singularity, inflation, the creation of neutrons and protons out of quarks, and the formation of the first elements.

2.2 Big Bang nucleosynthesis

Theoretical calculations of nucleosynthesis during the Big Bang show that the relative abundances of the elements are very sensitive the amount of radiation present. If we can determine the primordial abundances then we can pin down the amount of radiation and the amount of normal matter. That means we can determine two of the components of the Friedmann equation.

2.3 Baryon-to-photon ratio

The oldest objects in the Universe that we can study are old stars in our galaxy and high red-shift quasars. Spectroscopic observations of these objects tell us the abundances of the elements as they were created in the Big Bang. These elements were essentially just hydrogen and helium, with tiny amounts of deuterium and lithium. The data enable us to pin down the key physical parameter of the ratio of baryons to photons. This turns out to be around 6×10^{-9} or roughly 1.7 billion photons for every baryon (proton or neutron).

2.4 Cosmic microwave background

The cosmic microwave background (CMB) is observed to be uniform across the sky with a temperature of 2.73 K. The uniform nature of this thermal radiation tells us the number density of photons at the time of the CMB. This is the energy density of radiation. We can extrapolate this back to the time of nucleosynthesis where we finally arrive at the number density of photons then.

2.5 Baryon density (Problem 1)

Knowing the baryon-to-photon ratio (from 2.3 above) and the number density of photons (from 2.4 above), we can work out the number density of baryons at the time of nucleosynthesis when the elements were formed. This then gives the amount of normal matter at the time of the CMB and this turns out to be only 10% of the density of matter required for a flat Universe. This is Problem 1. Something else must be contributing the other 90% of the matter to make the Universe flat.

2.6 Age of Universe (Problem 2)

Spectroscopic observations of stars in the Milky Way and in the surrounding globular clusters, coupled with stellar evolutionary theory, show that the oldest stars are at least 12 billion years old. The Universe cannot be younger that the stars in it; so physical cosmology must explain why the Universe is a good deal more than 12 billion years old. When the known densities of radiation and normal matter are plugged into computer models, such as the ΛCDM model, the age of the Universe comes out far too small, perhaps just 7 billion years. This is Problem 2. Some other factors need to be added to the models to bring the age of the Universe up to our current best estimate of 13.8 billion years.

2.7 Baryon acoustic oscillations (Problem 3)

` The cosmic microwave background (CMB) comes from a time when the Universe was around 380,000 years old. It shows minute fluctuations in the temperature at a level of around one part in one hundred thousand (~10^{-5}). The power spectrum of these fluctuations shows a number of peaks that are interpreted as coming from acoustic oscillations in the normal matter. Computer models cannot reproduce peaks for a Universe containing only matter and radiation. This is Problem 3. Something else has to be added to the computer models to make them agree with the observations.

2.8 Flat Universe (Problem 4)

Inflationary theory drives the Universe to being flat. The appearance of the CMB also indicates the Universe to be flat. Hence the expansion of the Universe is governed by the Friedmann equation. But the known energy densities of matter and radiation are too small by a factor of at least five. The Universe should be open and not flat. This is Problem 4. Some other factor has to be added to the Friedmann equation to make the Universe flat.

3 The Dark Matter Solution

3.1 All four problems can be resolved by the addition of extra matter which, by the very nature of the problems, cannot be normal baryonic matter. So the dark matter solution is simply to propose the existence of between 5 and 10 times as much non-baryonic matter as normal baryonic matter. The equations, models, and calculations are all short of gravitating matter; so when dark matter is added the total mass is brought up to the right level.

3.2 Problem 1 - Big Bang nucleosynthesis. The theoretical calculations for the abundance of the elements only match the observed the observed values if normal baryonic matter is just 10% of the critical energy density. So by adding in 90% as non-baryonic dark matter, the energy density reaches the critical value, and the calculations give the observed numbers.

3.3 Problem 2 - age of the Universe. Computer models for the evolution give too young an age. So we again add in a large amount of dark matter, essentially into the Friedmann equation. The energy density goes up and the computer models, including the ΛCDM model, give a much older Universe, with the age coming in at the required 13.8 billion years.

3.4 Problem 3 - baryonic acoustic oscillations. The early Universe needs gravitational wells in which the normal matter can generate sound waves; the baryonic acoustic oscillations. So we add in a large proportion of dark matter, which is not affected by the high temperature plasma, and this happily clumps together to form the required gravitational wells.

3.5 Problem 4 - flat Universe. With just normal matter and radiation the energy density is way below the critical density and the Universe cannot be flat. So by adding in a large amount of dark matter, the energy density becomes critical, and we end up with a flat Universe.

3.6 An important point is that the amount of dark matter we need to add to solve all four problems is roughly the same. We have four independent problems and so we would naturally expect to to require four different amounts of dark matter. But adding around five to ten times the amount of normal matter as dark matter we can solve all four problems. This is a very persuasive argument in favour of dark matter.

4 Summary

4.1 The addition of around 5 to 10 times as much dark matter as normal matter solves a number of cosmological problems.

4.2 Problem 1. Dark matter provides the extra density required at nucleosynthesis (just after the Big Bang) so that the baryon-to-photon ratio agrees with observations.

4.3 Problem 2. Dark matter fixes the expansion of the Universe problem so that the Universe is older than the stars in it.

4.4 Problem 3. Dark matter provides the gravitational wells required to generate the peaks in the power spectrum of the cosmic microwave background.

4.5 Problem 4. Dark matter brings the overall density up to the critical density that is required for a flat Universe.

4.6 Overall there is no doubt that the dark matter hypothesis provides a very compelling solution to key problems of physical cosmology.

10

The Growth of Structure

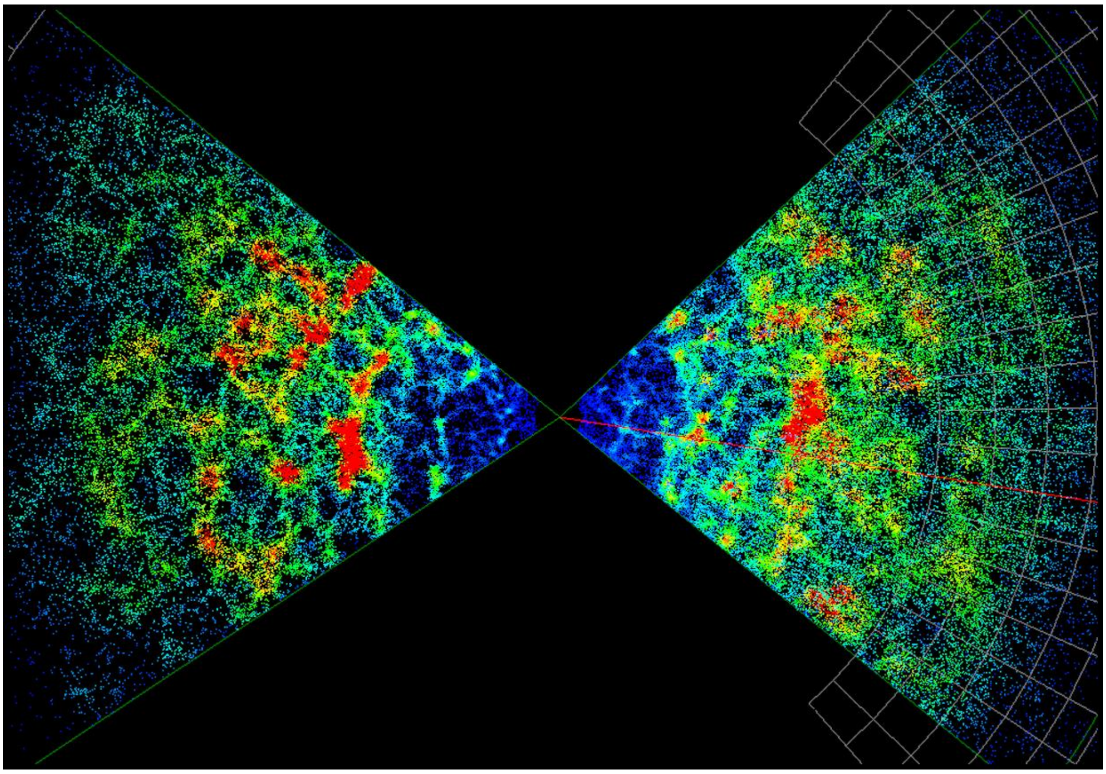

Figure 10.1. Distribution of galaxies in the Universe centred on our location. Image shows the galaxies are not uniformly distributed but have evolved into filaments, walls and voids. (Credit: The 2df Galaxy Redshift Survey Team)

We look at the growth of structure in the Universe and ask the question "how does dark matter solve the problem of structure growth?"

1 Introduction

1.1 At the time of the cosmic microwave background (CMB), the normal matter in the Universe was spread out with an almost perfectly uniform density. There were no structures at all. Today the Universe is full of structures: stars; galaxies; clusters of galaxies; filaments; voids. All these have been formed by gravity gradually pulling matter together into larger and larger clumps. Regions with a very slight excess of matter attracted more matter to them and, over a long period of time, they grew into the large structures we see today. The growth was bottom up with small objects forming first and large objects later. So first stars, then galaxies, then clusters of galaxies.

1.2 The cosmic microwave background shows that at 380,000 years after the Big Bang the differences in density between regions were about one part in 100,000. That is a very small difference and suggests that gravity needed a very long time for small density enhancements to grow into anything substantial.

1.3 The earliest stars are thought to have formed by the time the Universe was a few hundred million years old. The earliest galaxies had formed by 1 billion years; clusters of galaxies by a few billion years. The question arises as to whether or not there was sufficient time for normal matter on its own with just gravity to build such objects.

2 Observational Data

2.1 Observations of the cosmic microwave background show that normal matter had an essentially uniform density at 380,000 years after the Big Bang. The fluctuations in the density of normal matter were no more than 1 part in 100,000.

2.2 Observations of the rate of expansion of the Universe put its age at around 13.8 billion years. Analysis of the oldest stars associated with the Milky Way (those found in globular clusters) shows they are at least 13 billion years old. So stars were in existence well before the Universe was 500 million years old. Computer models suggest the first stars were created much earlier, perhaps even before 200 million years.

2.3 Observations of the red shifts of the remotest galaxies by the Hubble Space telescope show that some galaxies had formed by the time the Universe was 1 billion years old.

2.4 Figure 10.1 shows the distribution of galaxies around our location as determined by the 2dF Galaxy Redshift Survey. It is clear that the distribution is not uniform and that large scale structures have developed, such as walls, filaments, and voids.

3 Chain of Reasoning

3.1 Structures grow through gravitational instability; regions with slightly higher density pull in more material by gravitational attraction and so get more dense. The theory behind such growth suggests that density enhancements go with the red-shift. The red-shift at the time of the cosmic microwave background (recombination) was around 1190. So the expected enhancement in density today is not expected to be greater than a factor of 1190.

4 The Problem

4.1 At the time of the CMB, some 380,000 years after the Big Bang, normal matter was smooth to around 1 part in 100,000. Gravity on its own could not have pulled the matter together and formed any structures in the time available. Some other agent is required.

4.2 For example gravity acting on normal matter requires many billions of years to form galaxies. Yet galaxies were in existence by the time the Universe was just one billion years old.

5 The Dark Matter Solution

5.1 Dark matter is not affected by the same forces as normal matter; it does not interact with radiation nor is it affected by electron scattering. So, unlike normal matter, there is nothing to stop it forming structures and gravitational wells prior to the time of the cosmic microwave background (CMB).

5.2 So well before the time of the CMB the Universe was full of clumps of dark matter. These were the gravitational wells that were the seeds on which normal matter would form structure.

5.3 As soon as normal matter became neutral, at the time of the CMB, it started falling into the gravitational potential wells already created by dark matter. This kick-started structure formation and enabled normal matter to catch up for lost time.

5.4 With 5 to 10 times more dark matter than normal matter, dark matter had a much greater gravitational influence on pulling normal matter together. Normal matter would have formed objects in exactly the same locations as dark matter.

5.5 With dark matter in place there are no longer any problems with the time scales for normal matter to form stars, galaxies, and other structures.

6 Summary

6.1 There is insufficient time for stars and galaxies to form through gravity acting on the initial density fluctuations of normal matter. Something else has to be involved.

6.2 The addition of five to ten times as much dark matter as normal matter means gravity has the extra helping hand needed to form the observed structures. This process has been demonstrated by computations with the ΛCDM model of cosmology.

11

The Conjecture

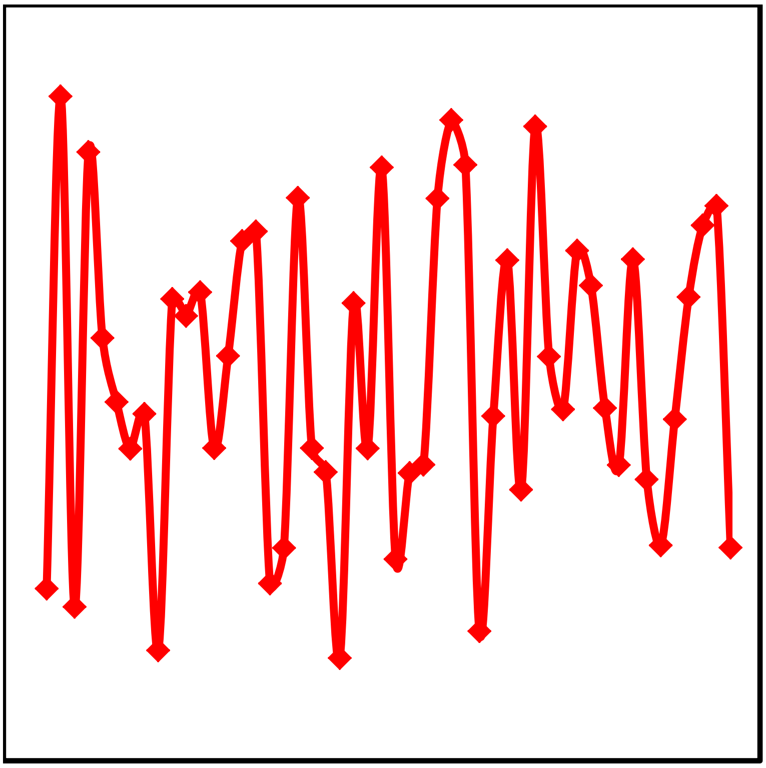

Figure 11.1. An example of random variation.

We put forward a new idea to replace the idea of dark matter.

1 Dark Matter Summary

1.1 If you're a diligent reader you will have got here by dogged determination and should now have a good grasp of dark matter and those astronomical situations where its existence is called into play.

1.2 On the other hand you may be a scoundrel (or a knowledgeable scientist - is there a difference?) and have jumped straight in here to get at the meat.

1.3 Whatever. It does no harm to summarise why everyone thinks dark matter is, in astronomical terms, "the best thing since sliced bread".

1.4 There are a large number of astronomical situations, involving gravity, where there doesn't appear to be enough matter to explain what is going on. The deficit is huge, something like five times the mass of all the observable matter appears to be missing. The deficit is roughly the same in all cases, whether it is spiral galaxies, galaxy clusters, or the Universe at the time of the cosmic microwave background.

1.5 The hypothesis that around 85% of the matter in the Universe is dark matter solves all the missing matter issues at a single stroke. This one ad hoc postulate fixes them all. This is a strong argument in favour of dark matter. There should be no doubt about it; dark matter really does do the business.

1.6 Nevertheless, there are a number of nagging doubts that are beginning to creep in, which is why we need to keep looking for alternative solutions. A few of these doubts are

1. Dark matter cannot be baryonic and if it is a particle then is must be a new particle beyond the standard model of particle physics.
2. Despite extensive searches and experiments no dark matter particle has ever been detected.
3. Despite enormous effort no one has managed to modify general relativity so that it accounts for the observations.
4. I don't believe in it (this is an extremely bad reason and is completely unscientific).

1.7 With that it's now time to move on to our new idea for solving the dark matter problem.

2 The Conjecture

The energy scale can vary from location to location

3 Explanation

3.1 The above conjecture means that the energy scale is not a fixed absolute immutable scale. It can change from one time to another and from one place to another. Others may prefer to call this "a hypothesis" but for us "conjecture" has a nicer ring to it.

3.2 We are calling it "a conjecture" because it is both speculative and incomplete. In atomic physics we can explain observations involving electrons because we have a theory for the electron and the theory works. We do not have a similar theory that explains how the energy scale might vary. Also, at the moment, we cannot demonstrate that energy scale variations actually exist. The best we can do is to state that "one way of explaining a large number of astronomical and cosmological observations is to postulate the existence of variations in the energy scale".

3.3 Figure 11.1 show a quantity that varies about some average value in a random fashion. There is no underlying theory that explains these variations. What we would like to have is an energy scale that varies in a way that is understandable in terms of a proper scientific theory. Furthermore we would like such a theory to make predictions that can be tested against observations. The theory must be falsifiable.

3.4 Our conjecture above is very clear and very simple. However, being clear and simple is no guarantee of being correct. As HL Mencken put it

> *"there is always a well-known solution to every human problem - neat, plausible, and wrong."*

Nevertheless we will stick with our clear and simple conjecture because a number of explanations to difficult problems follow from it.

3.5 All measurements of energy are made relative to some energy standard, and this standard will relate back to some physical constants. If the energy scale varies in a particular location then the observed values, the local energy standards, and the underlying physical constants all vary in step with one another. So the effects cancel out and the measurements of the energy end up with exactly the same values as before; there are no detectable differences. So how can this possibly help us in providing an alternative explanation for dark matter?

3.6 Most of us are familiar with the three scales of mass, length, and time. A few of us may also be aware of scale for electric charge. We can think of energy as a generalised kind of mass. So we can think of the energy scale as being more or less the same thing as the mass scale.

3.7 The idea of an energy scale is a new concept to most people. And the idea that a scale might vary is equally likely to be a new concept as well. The next few chapters look at these concepts as a preparation to understanding how the above conjecture does away with dark matter. And to get to this new understanding we need to go right back to basics and take a fresh look at some ideas that we were taught in our earliest lessons in primary school.

4 Summary

4.1 We propose that the energy scale is not fixed but varies from location to location.

4.2 Both the length scale and the time scale are fixed; they do not vary in any place or at any time.

4.3 The speed of light does not vary, it is an absolute constant.
The gravitational constant does not vary, it is also an absolute constant.

12

Measurements

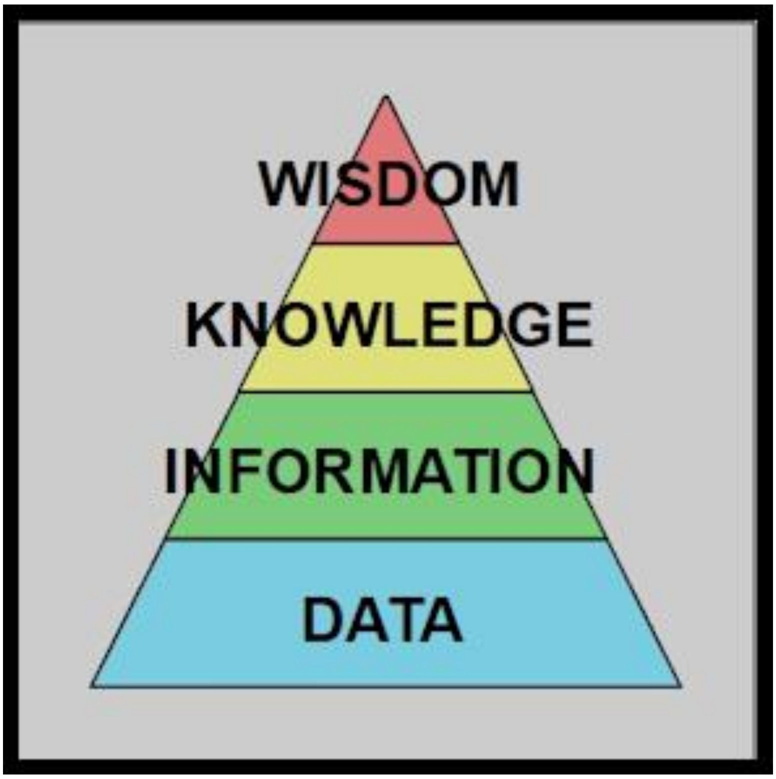

Figure 12.1. The wisdom hierarchy.

We get back to basics and look at science, scales, units, measurements, errors, and equations.

1 Science

1.1 Science is a human activity that attempts to explain how the world works and, by extension, the Universe beyond. Getting to these explanations involves a host of disparate items including: observations; measurements; data; information; numbers; graphs; equations; maths; theories; logic; and more. Putting this lot together gives us the so-called scientific method, although in practice much of it comes down to plain trial and error.

1.2 Fortunately, or unfortunately, applying the scientific method to get at an explanation for how something works is a task that never ends. There are always people trying to prove it wrong; there are always new tests to be carried out; there is the ever-present mantra "better is the enemy of best" that leads to the perpetual search for something beyond what we've got. We only have to look at Einstein's general theory of relativity which has been under constant scrutiny for over one hundred years (and still passing tests with flying colours).

1.3 We can take the example of planetary motions. Ancient civilisations believed that the planets revolved in circular orbits around the Earth; this was a good enough explanation for them and it fitted their observations. When the observations improved it became necessary to add circles (epicycles) to the circles and with these the underlying explanation of everything revolving around the Earth still held. Eventually, many centuries later, with the arrival of Copernicus, a new explanation came along, namely that the Earth and planets revolve around the Sun. And later, following Kepler, the circles were replaced with ellipses. Newton's law of gravitation, coupled with his laws of motion, explained all the observations mathematically and these stood for a few hundred years before a tiny discrepancy in Mercury's orbit crept in. Einstein's theory of gravity, general relativity, eliminated this discrepancy and once again we had an explanation that accounted for all the observations. But we are not finished. New observations are being made and we have discrepancies creeping in again with minute details in the motions of the outer planets and the Pioneer space probes. Perhaps general relativity is not the last word in gravity; perhaps there are more planets beyond the orbit of Pluto; perhaps there is something else.

1.4 There are many different ways of improving our knowledge of how things work. Business (especially information technology) and education (learning) often make use of the wisdom hierarchy, shown as the pyramid in Figure 12.1. We start at the base of the pyramid with data and hopefully ascend until we reach wisdom. So data leads to information; information leads to knowledge; and knowledge leads to wisdom.

1.5 For example. Is the number 12349876 divisible by 11? Our eyes see the eight symbols on the page (the data) and our brains recognise them as a number (the information). We have the knowledge that if the sum of the even digits (1+3+9+7=20) matches the sum of the odd digits (2+4+8+6=20) then the number is divisible by 11. So, yes, 12349876 is divisible by 11. But, for many of us we do not understand, or have forgotten, why the rule works. We have the knowledge but are lacking that final bit of wisdom.

1.6 The wisdom pyramid is a useful way of looking at things in some areas, but it is perhaps more useful as a stimulus to make us think about progressions. The wisdom hierarchy illustrates how the scientific method leads to explanations, and these explanations may or may not be correct.

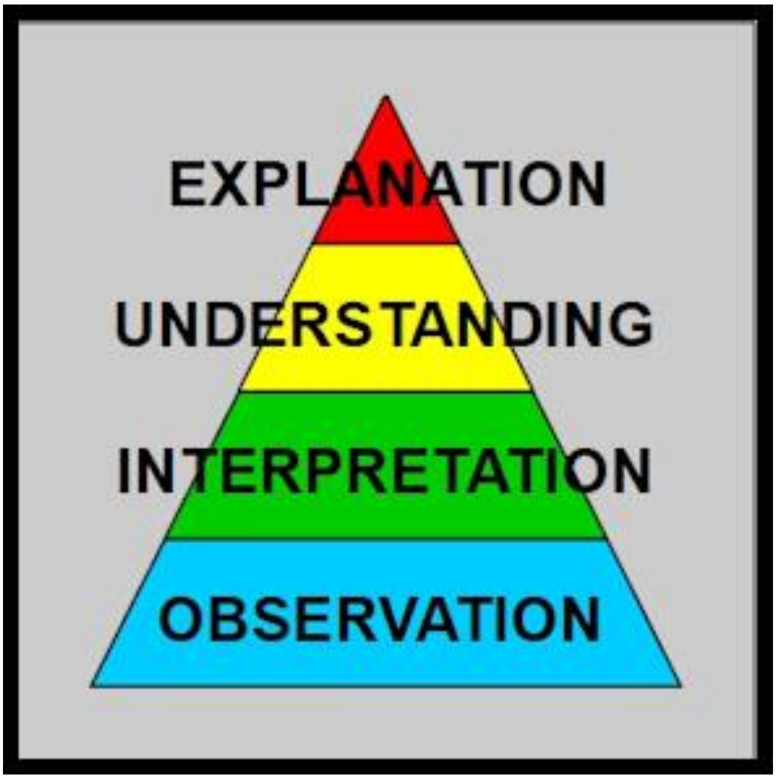

Figure 12.2. The explanation pyramid

1.7 For example: I came up with my own wrong explanation of a physical situation involving the weather. I noticed that after a spell of warm weather it would start raining and the temperature would fall. I naturally concluded that the rain caused the drop in temperature. This was completely wrong because it is the other way round. The temperature falls, the moisture condenses into water droplets, and it starts raining.

1.8 My own take on the wisdom hierarchy is to work with a different progression, shown as the pyramid in Figure 12.2. This time we move up the pyramid by answering a different question at each stage. We start with the observations and get to interpretation by answering the question "what is going on?" We move from interpretation to understanding by answering the question "does it make sense?" i.e. do we understand the observations in terms of our current theories. Finally we get to explanation by answering the question "can we build a coherent consistent explanation for the observations?" This is kind of going in the other direction. We, as individuals, may have an understanding that works for us in our own terms but the job is not done until we have an explanation that we can communicate to others so that they also understand. So teaching is as important as learning.

1.9 We can look at how this pyramid works with dark matter. We have numerous observations of spiral galaxies and their rotation curves (observation). For "what is going on?" (interpretation) we have: the stars & gas in a spiral galaxy revolve around the galaxy centre; the speed in the outer regions is roughly constant. For "does it make sense?" (understanding) we have: Newton's law of gravity predicts that the speed in the outer regions should decrease, so the observations of a constant velocity do not make sense and we have a problem with our understanding. For "can we build an explanation?" (explanation) we have the hypothesis of dark matter and that spiral galaxies are surrounded by a dark matter halo, which gives rise to the constant velocities. Thus dark matter gives a consistent and coherent explanation of the observations, and with that everything is alright again.

1.10 Before we get too far into our scientific method there is a spanner that gets thrown into the works, courtesy of Donald Rumsfeld's notorious quote (given as US Secretary of Defense 12th Feb 2002):

> *"Reports that say that something hasn't happened are always interesting to me, because as we know, there are known knowns; there are things we know we know. We also know there are known unknowns; that is to say we know there are some things we do not know. But there are also unknown unknowns – the ones we don't know we don't know. And if one looks throughout the history of our country and other free countries, it is the latter category that tend to be the difficult ones."*

This is logically correct but also very confusing at the level of the English. It can be clarified by changing the first "know" to "aware", so that "we know we know" becomes "we are aware we know".

1.11 The unknown unknowns issue can be explained using the following decision table.

	know	**don't know**
aware	things that we are aware that we know	things that we are aware that we don't know
unaware	things that we are unaware that we know	things that we are unaware that we don't know

I have replaced the first word "know" with "aware", just to get rid of the confusion. Rumsfeld omitted the bottom left cell; the things that we are unaware that we know (unknown knowns). An example of this is the whodunit murder mystery. We have all the facts needed to identify the murderer but we usually fail to do so and need a Sherlock Holmes character to unmask the guilty party.

1.12 The spanner in the works is the problem of what happens when the fact, the thing that we are aware that we know (the known known), turns out to be wrong; when what we thought was true turns out to be false. An example is the political fallout following the 2003 Iraq War: the West went to war with Iraq on the basis that Saddam Hussein possessed weapons of mass destruction. He didn't and this "fact", this "known known", turned out to be untrue.

1.13 The get out clause for this is that a theory (or hypothesis) can only be called scientific if it is falsifiable, that is if the theory is testable and experiments can be carried out to check whether it is right or wrong. A good theory should make predictions so that new experiments can be carried out that allow it to be tested.

1.14 In chapter "2: Eureka!" paragraph 1.10 we quoted Richard Feynman's argument that if we have a law that does not agree with the observations then the law is wrong. Newton's law of gravity does not agree with the observed rotation curves of spiral galaxies. In Feynman's terms it is wrong and we should abandon it. A few scientists do want to ditch Newton's law of gravity in favour of a new theory but needless to say this has not happened. The vast majority of scientists are content to rescue Newton's law of gravity by the ad hoc addition of dark matter.

1.15 Currently dark matter seems to lie very much in the top left cell of "things we are aware that we know". The vast majority of scientists accept that dark matter exists and that the case for dark matter has been proved beyond reasonable doubt. Numerous books and articles now contain categorical statements such as "we know dark matter exists". For these scientists the only problem is trying to pin down exactly what the particle is and to detect it in an experiment. There are a few dissenting voices that hold the opposing view that dark matter does not exist and that the problem lies with our theory of gravity (general relativity).

1.16 Before we meander too far from what this book is about we should return to our concern with dark matter. We have a fair number of independent astronomical phenomena, all of which indicate there is more mass present than our observations show. We can understand all the observations under the assumption that there exists additional mass in the form of dark matter. We have to acknowledge that dark matter does a really good job in explaining all the observations.

2 Scales

2.1 We humans seem to take delight in drawing up lists (e.g. presidents of the United States; highest mountains in the world; top 100 films) and putting things into categories (e.g. types of tree; classes of animal; makes of motor car). This also happens with science where we have all sorts of scales (e.g. Beaufort scale for wind speeds; Richter scale for earthquakes). Over the centuries different scales have come and gone in popularity.

2.2 The ancient Greeks proposed that the nature of matter was determined by four scales - the essences: earth; fire; air; water. The stars and heavenly bodies (Sun, Moon, planets, comets, etc) were determined by a fifth element: quintessence. The properties of any object could then be explained in terms of how much it contained of each essence.

2.3 Medieval medicine had the idea that the human body was characterised by four scales - the humours: blood; yellow bile; black bile; phlegm. These also corresponded to the four temperaments: sanguine; choleric; melancholic; phlegmatic. Illnesses were then attributed to the humours being out of balance with one another. The patient was cured by restoring the balance and this often led to some interesting options by today's standards such as: herbal potions; blood-letting; witchcraft; religious relics; prayers.

2.4 Psychology labels people by placing them on a scale from completely introvert to completely extrovert. Alternatively we characterise a person's personality as either Type A (competitive, high stress) or Type B (relaxed, low stress). We do not yet have a theory for the brain, so psychological profiles are somewhat limited. Although rapid advances are being made through the use of MRI and other brain scanners, a complete theory of the brain is probably still 50 years away. Nevertheless in the next few years we can expect huge changes in how mental disorders are characterised and treated.

2.5 Astrology is still thriving and a large fraction of the population still read their horoscopes, where their fortunes are supposed to be influenced by the planets and the stars. Here the future for an individual is controlled by a scale containing the 12 signs of the zodiac. Whether individuals actually believe in horoscopes is an open question, but many undoubtedly take note of their predictions, which then end up as self-fulfilling prophesies.

2.6 Modern science continues these trends and assigns its own properties to quantities through the use of 7 scales: mass; length; time; electric current; temperature; luminous intensity; amount of substance. Every quantity that physics measures is done so in terms of these 7 scales; these are listed in Table 12.1 below.

Scale	Scale Symbol	Standard Unit	Unit Symbol
Mass	M	kilogram	kg
Length	L	metre	m
Time	T	second	s
Electric current	I	Ampere	A
Temperature	K	Kelvin	Θ
Luminous intensity	J	candela	cd
Amount of substance	N	mole	mol

Table 12.1. Scales used by the International System of Units.

2.7 For example: volume has the units of length cubed; speed is length divided by time; energy is mass times length squared divided by time squared. With our own take on science and logic we tend to deride the ideas of previous eras but that may well prove to be exceedingly arrogant. It will be surprising if, a few hundred years hence, future scientists are still using our scales; instead they will probably smile to themselves over our quaint ideas.

2.8 If we label: mass as "earth"; length as "water"; time as "air"; electric charge as "fire"; then we can see that the ideas of ancient civilisations, in describing objects in terms of earth, fire, air and water, are not quite so unenlightened as we might think. Or, put another way, we are not really any smarter than they were.

2.9 For the rest of this book we are working with just the three scales of length, time, and mass (energy). A list of physical quantities and the units that constitute them is given in "32: Quantities and Units" at the end of the book. It is truly remarkable that such a large number of different physical quantities can be expressed in terms of just these three scales. Length, time and mass are sufficient to define such diverse quantities as: area; force; power; acceleration; angular momentum; pressure; energy; and more.

3 Units

3.1 Whenever we buy anything we have to be aware of the units. We do not just give a number but specify the units as well. If we don't then we may not get what we want. The result of asking for "3 potatoes" is very different from "3 kilograms of potatoes". And we very quickly learn to specify the units when we hand over cash to pay for things. If we simply pay "20" for some item then this could be an expensive mistake should we hand over "20 euros" for something costing "20 cents". So when trading we see that the units are important.

3.2 In physics whenever we measure anything we are always conscious of the units and not just the number. So we have:

the speed of light is $3x10^8$ metres per second;
the energy of the Hiroshima bomb was equivalent to 15,000 tons of TNT;
the boiling point of water is 100 degrees centigrade;
the area of Wales is 8,000 square miles;
a spider has 8 legs;
the population of Russia is around 150 million people;
the time for light to cross the Earth's orbit is 1000 seconds.

Physics cares about the units; maths does not.

3.3 As mentioned above above physics uses seven scales for measuring quantities. From this point on we will only be interested in three of them, namely: length; time; mass.

3.4 For each of these three scales we need a single standard that can be used for making measurements. Physics has adopted the International System of Units or simply SI units

mass has the kilogram, kg; defined by a lump of platinum-iridium alloy.
length has the metre, m; defined by the distance light travels in 1/299709458 second.
time has the second, s; defined by the time for a transition of the caesium-133 atom.

Such standards ensure that the measurements made by different scientists working in different parts of the world are commensurate and can be compared directly with one another.

3.5 Historically many physical quantities have been measured on their own, without reference to other quantities, and as such have evolved their own units of measurement. Most of these units are still in use today. So in everyday use we continue to work with:

litres or gallons for measuring liquids;
acres or hectares for land area;
millibars for atmospheric pressure;
knots for speed at sea and in the air;
kilocalories for food energy;
Pascals for pressure - after Blaise Pascal;
Newtons for force - after Isaac Newton;
Watts for power - after James Watt
Hertz for frequency - after Heinrich Hertz

In principle we could do away with all of these and work purely in terms of the standard units. But this would make life somewhat dull and somewhat uninteresting.

4 Measurements

4.1 We have looked at scales and we have looked at units, so we can go right ahead and start making measurements.

4.2 When we want a new pair of jeans we get out a tape measure and measure our waist size. But where did the markings on the tape measure come from? And if the jeans are made in China how do we know their measurements are the same as ours and that the new jeans will fit?

4.3 All measuring devices have to be calibrated against a standard. Almost certainly this will not be the official SI standard but a secondary standard. So in the case of our tape measure, at some point during the manufacturing process it was compared to a standard and the centimetre markings put in place.

4.4 This means we are in fact measuring the ratio of a distance interval on our tape measure to another distance interval on the standard. A ratio of two identical quantities is a dimensionless number, i.e. a pure number with no units.

4.5 It is important to realise that whenever we measure anything in practice we get a pure number. We can only attach units to the number because our measuring device has been calibrated.

4.6 It is also important to realise that the different scales are unique. For example there is only one length scale. When we measure our height we end up with a number of centimetres (cm). When we see how fast our car is going we end up with a number of kilometres per hour (km/hour). The two length components, cm and km, are on the same overarching length scale. There is not one length scale for use in heights and another length scale for use in speeds; there is only one.

4.7 When, in Star Wars, Han Solo, aboard the Millennium Falcon, made the Kessel run in a distance of 12 parsecs he was using the same length scale as applies here on Earth. He had no choice; there is only one length scale and it is universal; it applies everywhere, not just on Earth but also in faraway galaxies.

4.8 Without exception, the measurement of every physical quantity involving length can be mapped back to the single unique length scale. A similar situation applies for the scales of mass and time. There is only one mass scale; there is only one time scale.

5 Errors

5.1 We need to have a look at errors.

5.2 We all make mistakes with arithmetic but proper errors do not seem to occur in maths. We never talk about π as being 3.14 ± 0.01; π is always its exact irrational numerical self and the idea of it having an error is completely out of the question.

5.3 On the other hand in physics just about all numbers are subject to errors. These errors crop up all the time and they are really important. Measurements can only be made to a limited accuracy, and often this accuracy fixes the size of the error. You cannot use a metre rule to measure lengths to the nearest micron; the best you can probably do is to the nearest millimetre, mm. So whenever you measure a length with a metre rule it is always ±1 mm.

5.4 Errors are really important in deciding whether or not an experiment has come up with something new. If the measurements are within the errors then the experiment has not found anything new. However, if the measurements find something that is way outside the errors then there is definitely something that needs further examination and maybe even a new discovery.

5.5 In any experiment we need to understand what determines the errors; what statistics we should apply; what the probability distribution is. Two examples should clarify this point.

5.6 Firstly, with a deck of playing card we have 52 cards and the chance of picking any particular card is 1 in 52. The probability distribution is flat and every card has the same probability of being chosen.

5.7 Secondly, with human males we have a range of heights. However, not all heights are equally probable and the distribution is strongly peaked around an average height of 1.8 m. So the chance of picking a man of height 1.8 m is much greater than either 1.4 m or 2.0 m. Unlike playing cards the heights for a man are not all equally likely. The probability distribution for heights is not flat but is the so-called "bell shaped curve" with a central maximum.

5.8 So it is important to remember that when an event occurs you cannot say anything about its likelihood unless you have a probability distribution. This applies to earthquakes, volcanic eruptions, as well as to the chance of detecting new particles at the LHC.

6 Equations

6.1 We now have to get our hands a tiny bit dirty by looking at equations. We will not have to do any maths but it is important that we understand the structure of equations and what they are about.

6.2 An equation, as the word implies, is an expression stating there is a relationship of equality between two things.

6.3 There are different types of equation and what we usually think of as an "equation" is an "algebraic equation" where we have equality between two algebraic expressions. We learn to write this as

$$\textbf{left-hand side} \;=\; \textbf{right-hand side} \tag{12.1}$$

A simple example is Pythagoras' theorem for a right-angled triangle

$$\boldsymbol{a^2 \;=\; b^2 + c^2} \tag{12.2}$$

where the square of the hypotenuse, $\boldsymbol{a}$, equals the sum of the squares of the other sides, $\boldsymbol{b}$, $\boldsymbol{c}$.

6.4 Unfortunately the equals sign "=" has been hijacked by computer programming languages where their codes and algorithms are full of expressions such as

$$\boldsymbol{x \;=\; x + 1} \tag{12.3}$$

If this was an algebraic equation it would clearly be nonsense. Instead it is not an algebraic equation at all but an "assignment statement" telling the computer to add 1 to the value of x and set x to that new value.

6.5 In paragraph 6.2 above we used the word "relationship". There are many different relationships between things and equality is just one of them. So we can have: $\boldsymbol{x > y}$ (greater than); Elon Musk drives a Tesla car (drives); librarians like books (like). Nowadays the information in these relationships is often grabbed by technical & financial companies, where algorithms & data analytics do their work. Different information is then fed back to us to "help" us with our life choices.

6.6 Equations also embody the idea of balance. Whatever is on the left hand side must balance whatever is on the right hand side. It is this balance that enables us to simplify equations or even solve them. For example

$$\mathbf{5(2x - y + 3) - (x + 7y + 9) \;=\; 3(3x - 4y + 2)} \qquad (12.4)$$

By inspection we can verify we have the same number of $\boldsymbol{x}$'s and $\boldsymbol{y}$'s on both sides; the equation is balanced.

6.7 Another type of equation is the chemical reaction, which is instructive for us. Chemical reactions also balance and the numbers of the elements on both sides must be the same. For example: when methane (CH_4) burns with oxygen (O_2) in the air we end up with carbon dioxide (CO_2) and water (H_2O). We know the chemical equation must have the form

$$?\,\boldsymbol{CH_4} + \;?\,\boldsymbol{O_2} \;=\; ?\,\boldsymbol{CO_2} +\; ?\,\boldsymbol{H_2O} \qquad (12.5)$$

but we have to work out what numbers the "?" stand for. In this case the solution is straightforward and we have

$$\boldsymbol{CH_4} \;+\; \mathbf{2}\,\boldsymbol{O_2} \;=\; \boldsymbol{CO_2} +\; \mathbf{2}\,\boldsymbol{H_2O} \qquad (12.6)$$

By inspection, we see we have the same number of hydrogen atoms (H=4), carbon atoms (C=1), and oxygen atoms (O=4) on each side. We have a balanced equation.

6.8 We now return to the matter in hand, namely physics equations. One of my ways of describing physics is to say that "physics is maths plus units" (maths does not care about units). It follows that in a physics equation we must make sure the units balance on both sides, in exactly the same way as the elements must balance in a chemical reaction. For example: Newton's second law of motion is force, $\boldsymbol{F}$, equals mass, $\boldsymbol{m}$, times acceleration, $\boldsymbol{a}$:

$$\boldsymbol{F} \;=\; \boldsymbol{m} \times \boldsymbol{a} \qquad (12.7)$$

This is fine as an algebraic equation but, for a physics equation, there is not a unit in sight. We can get the units for each quantity from Table 32.2 (in chapter "32: Quantities and Units") and rewrite the equation putting the units in square brackets

$$\boldsymbol{F}[\boldsymbol{M}\,\boldsymbol{L}\,\boldsymbol{T}^{-2}] \;=\; \boldsymbol{m}[\boldsymbol{M}] \times \boldsymbol{a}[\boldsymbol{L}\,\boldsymbol{T}^{-2}] \qquad (12.8)$$

We can now see that the units, in brackets, on both sides of the equation balance.

6.9 A second simple example is provided by Einstein's relationship between mass, $\boldsymbol{m}$, energy, $\boldsymbol{E}$, and the speed of light, $\boldsymbol{c}$

$$\boldsymbol{E} = \boldsymbol{m} \times \boldsymbol{c}^2 = \boldsymbol{m} \times \boldsymbol{c} \times \boldsymbol{c} \tag{12.9}$$

If we rewrite this to include the units we have

$$\boldsymbol{E}[\boldsymbol{M}\,\boldsymbol{L}^2\,\boldsymbol{T}^{-2}] = \boldsymbol{m}[\boldsymbol{M}] \times \boldsymbol{c}[\boldsymbol{L}\,\boldsymbol{T}^{-1}] \times \boldsymbol{c}[\boldsymbol{L}\,\boldsymbol{T}^{-1}] \tag{12.10}$$

Again the units in brackets balance.
Einstein's insight into physics makes this equation magical, but at the level of the units there is no magic - the units simply have to balance.

6.10 A third example is provided by the technique of "dimensional analysis" where looking at the units helps us to come up with the correct equation for a physical system. The pendulum is a well-known example of this. Observations show that the period of a pendulum, $\boldsymbol{P}$, depends on the length of the pendulum, $\boldsymbol{l}$, the acceleration due to gravity, $\boldsymbol{g}$, and possibly the mass, $\boldsymbol{m}$. So we are looking for an equation along the lines of

$$\boldsymbol{P}[\boldsymbol{T}] = \boldsymbol{l}[\boldsymbol{L}]\ \boldsymbol{g}[\boldsymbol{L}\,\boldsymbol{T}^{-2}]\,\boldsymbol{m}[\boldsymbol{M}] \tag{12.11}$$

This equation is clearly wrong as it does not balance at the level of the units. However, we can get it to balance if we rebuild it as

$$\boldsymbol{P}[\boldsymbol{T}] = \boldsymbol{K} \times \sqrt{\frac{\boldsymbol{l}[\boldsymbol{L}]}{\boldsymbol{g}[\boldsymbol{L}\,\boldsymbol{T}^{-2}]}} \tag{12.12}$$

where $\boldsymbol{K}$ is a dimensionless constant. This also tells us that the period of the pendulum does not depend on the mass of the bob.

6.11 Dimensional analysis is a powerful tool. Next time you have to help someone with their physics homework, try dimensional analysis and make sure the units balance. You might find you can solve the problem without fully understanding the physics or maths involved.

7 Summary

7.1 The whole of the physical sciences work by making measurements of physical quantities, all of which can be expressed in terms of just seven scales. The primary scales are length, time, and mass; additional scales, such as electric current, are used for other quantities.

7.2 Every physical measurement has a numeric value and a unit; where the unit is related back to standard measures of the seven scales.

7.3 The laws of physics can be expressed as mathematical equations where the units on both sides must balance.

7.4 Science advances by discovering new laws and by replacing old explanations with new explanations. Occasionally existing laws are found to be wrong, but such occasions are rare. The process is usually one of continuous refinement of existing laws and of gradual convergence towards better laws.

13

Constants

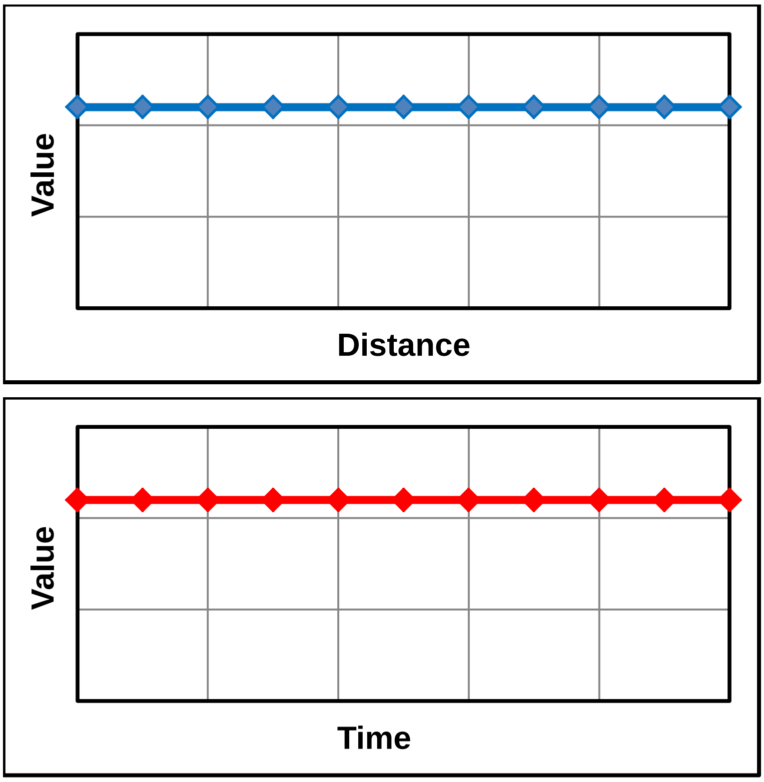

Figure 13.1. Illustration of a constant value that changes neither with distance nor with time.

We look at physical constants and ask the question "do any of the constants vary?"

1 Physics equations

1.1 We have already looked at physics equations and seen the way they differ from algebraic equations in that physics equations involve units. A second important difference is that physics equations usually involve constants, often referred to as constants of nature. We can look at a few examples.

1.2 The equation of most importance to us in this book is Newton's law of gravity, where the force, $F(r)$, is proportional to the product of the masses, M & m, and inversely proportional to the square of the distance, r. It can be written as

$$F(r) = -G\frac{M\,m}{r^2} \tag{13.1}$$

There is a constant in this equation, namely G . which is the universal constant of gravitation.

1.3 A second equation is Einstein's relation between mass, m, and energy, E

$$E = m\,c^2 \tag{13.2}$$

The constant in this equation is c, the speed of light.

1.4 A third example is the relation between the frequency of a photon, ν , and its energy, E

$$E = h\,\nu \tag{13.3}$$

The constant here is h, Planck's constant.

2 Physical Constants

2.1 Constants crop up everywhere in physics. We mentioned some above. Other examples of constants are

Boltzmann's constant, k, in the ideal gas law
the specific heat of water
the coefficient of expansion of copper
the density of gold

2.2 None of the values for the physical constants are known a priori; we do not have any theories that can predict the values of any of them. They must all be determined by experiment and measurement. For example: the masses of the electron and proton are not defined by atomic theory or by quantum mechanics; they have to be determined by experiment. The standard model of particle physics is extremely successful but it still depends on experimental determination for the masses of all the particles.

2.3 As technology advances the precision of experiments improves and the constants get measured with greater and greater accuracy. For example: Newton's constant of gravitation: Newton's own estimate, circa 1680, was around 7×10^{-11} $m^3\ kg^{-1}\ s^{-2}$; Cavendish circa 1800 measured 6.74×10^{-11} $m^3\ kg^{-1}\ s^{-2}$; today we have $6.6741 \pm 0.0003 \times 10^{-11}$ $m^3\ kg^{-1}\ s^{-2}$, i.e. it is known to around 5 significant figures with an error of 3 in the last figure. So our value for the gravitational constant has changed with time. Of course, the gravitational constant itself has not changed; it is just our measurement of it.

2.4 So the measured values we have for all constants of physics change over time and hopefully converge towards the correct value. As far as we know none of the constants themselves are changing; it is just our measurements of them.

3 Variation of Physical Constants

3.1 The next question we might ask is how do we know the constants are fixed and do not change. This is not a question for theory but for practical experiment and observation. If any of our experiments give different values then there is the possibility that what we take to be a constant is not a constant after all.

3.2 If a constant in our theory turns out not to be a constant then we have no option but to change the theory.

3.3 All measurements of physical quantities are made relative to some standard. Many of the physical standards are based on practical measurements that can be repeated by anyone anywhere. For example, our time scale is based on a hyperfine transition within the caesium atom. So in principle observers on Mars could establish the same time scale by constructing their own caesium clock.

3.4 Over the years an enormous amount of hard work has been put in by large numbers of dedicated scientists to establish a set of standards. So we can have complete faith that the standards of measurement we now use are robust and trustworthy. Whenever we make a measurement using an instrument calibrated against one of these standards then we should not hesitate to believe the results.

3.5 Some scientists have looked into whether or not any of the constants of physics vary either in space or in time. Some of the physical constants that have been considered for variation include: the speed of light, c; the constant of gravitation, G; the fine structure constant, α. There is no generally accepted evidence from any of the studies for any variation in any constant. If any vary then it is at the limits of current measurements and detectability.

3.6 To be clear there is no firm evidence that any of the constants of physics changes. The constants are just that, constant.

3.7 Nevertheless should we think a physical constant is in fact variable then we can carry out experiments to measure its value. The measurements are compared against reference standards to give its value. There is an immediate ambiguity as to whether it is our constant or the standard that is varying. It has been argued that looking for variations in any physical constant is a meaningless exercise as any such variation is simply equivalent to a change of units.

3.8 Apparently the only way to look for variations is to work with dimensionless constants. For example: if we suspect the mass of the proton is variable then, rather than measure the proton mass, we instead measure the ratio of the proton mass to the electron mass. This would be the ratio of two masses and so be dimensionless.

3.9 The fine structure constant, α , is a dimensionless number. It is an important number in atomic theory and controls the spacing of certain spectral lines. Some observations of the spectra of distant quasars suggest that the value of α may have been slightly different in the distant past. This is the only case in recent years where the fixed nature of a physical constant has been brought into question.

3.10 From what we have just looked at it is clear that if any constant does vary then it is at the limit of what we can detect. We are talking about minute changes of much less than one part per million. This book is about dark matter where the missing mass problem shows a mass deficit across the Universe of at least a factor of five. It is clear that minute changes in constants of one part per million is not going to solve our problem. We are looking the something much bigger.

4 Fine-tuning

4.1 Separate from the question of whether any of the physical constants vary is the question of why they have the values they do. For example, why is the mass ratio of the proton to the electron 1,836? Why isn't it 25 or 75,000,000? If any of the physical constants had different values then our Universe would be changed and in most cases life would not be possible. This is the fine-tuning problem. We can look at a couple of examples.

4.2 We can consider what our Universe would be like if the Up quark was slightly heavier, or the Down quark slightly lighter. The neutron is made of two Down quarks and one Up quark. The neutron is heavier than the proton, which is made of two Up quarks and one Down quark. In normal circumstances the neutron decays into a proton. However, with a heavier Up quark the proton would be heavier than the neutron, and protons would decay into neutrons. We would then have a Universe containing nothing but neutrons and as a consequence there would be no protons; no atoms; no elements; no stars; and no life.

4.3 Similar arguments apply to all the particles that make up the Standard Model of particle physics. We cannot predict the masses of any of the particles; all have to be measured by experiment. But it seems that the masses have to lie in very narrow ranges in order for our Universe to have any structure at all. This is fine-tuning.

4.4 If the gravitational constant, G, was larger then stars would be hotter and have shorter lives. Life on Earth would not have had time to evolve before the sun stopped shining. If the gravitational constant was smaller then stars would not form at all or not get hot enough for fusion reactions to start. So in considering a variation of the gravitation constant this can only happen within a narrow window of values. This is another example of fine-tuning.

4.5 One way out of the fine-tuning problem is the multiverse, the idea that there are an infinite number of universes each with their own set of values for the physical constants. The anthropic principle then applies whereby the fact that we exist at all means our Universe must have values for the physical constants that enable life to develop.

5 Physics is Robust

5.1 We have looked at some of the foundations that support the structure of science. The conclusion we should draw is that overall physics is in pretty good shape.

5.2 The scientific method is robust. The progression from observation to interpretation to understanding to explanation is robust. It has feedback loops whereby any inconsistency leads to new observations, new interpretations, new explanations, and so on.

5.3 Our measurements are robust. In principle anyone of us can repeat any experiment and check that we get the same measurements as reported by others. This actually happens in a large number of cases. It happens even more in areas of front line research, such as dark matter.

5.4 Our units are robust. The fact that all quantities can be expressed in terms of just seven scales is robust. The standards that define the units for each scale are also robust.

5.5 The laws of physics are robust. They provide explanations for just about everything that has ever been observed. Importantly they are falsifiable, which means they are open to testing and scrutiny.

5.6 The constants of physics are robust. There is no generally accepted evidence that any of the constants of physics are not completely fixed.

5.7 Nevertheless physics is not complete and there is still much to do. For example, although quantum mechanics and general relativity work perfectly well in their own domains they are known to be incompatible with one another. So work is ongoing to find some form of quantum gravity.

5.8 One area we haven't looked at yet is the scales of physics. Are our scales of length, time, and mass robust? This question is addressed in the next few chapters.

6 Summary

6.1 Whether any quantity, that we consider to be a constant, varies is a matter for experiment and not for theory.

6.2 The constants of physics do indeed appear to be constant. Within the limits of our experimental tests none of them appear to vary either in space or in time.

6.3 The variation of any physical constant cannot be used to explain the observations currently explained by dark matter.

6.4 In this book we take it that the universal constant of gravitation, G , is an absolute constant. Its value is the same everywhere; it does not vary.

6.5 Little or no work has apparently taken place into whether or not the scales of physics vary. Nobody seems to have asked this question in recent times. This possibility is examined in the next few chapters.

14

The Length Scale

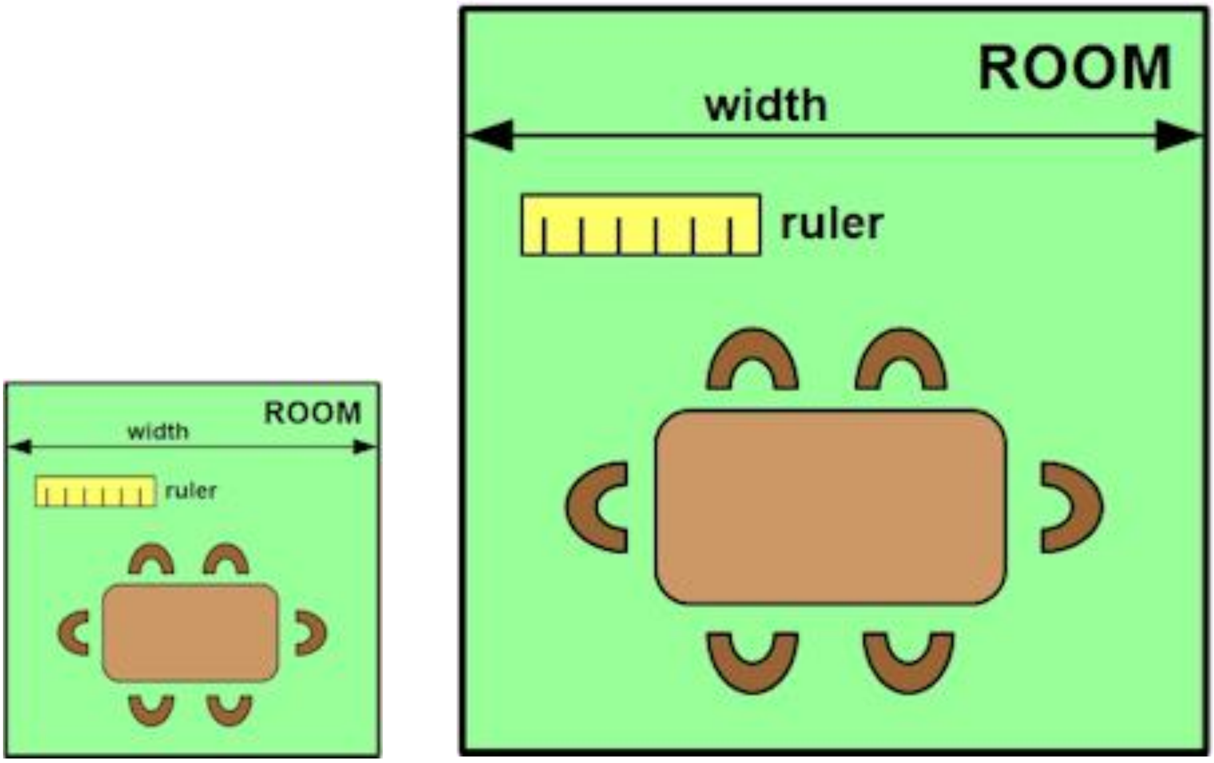

Figure 14.1. Measuring the size of a room when the length scale doubles in size.

We look at the length scale and ask the question "would we notice if the length scale varied?"

1 Length Scale

1.1 Length is the most basic of our scales. From Table 32.2 in chapter "32: Quantities and Units" we can see that length appears as one of the units in the majority of common quantities. Length is present in the quantities of: acceleration; angular momentum; area; density; energy; force; impulse; momentum; power; pressure; speed; volume. Length is absent from just: frequency; mass; time.

1.2 Our standard unit of length is the metre (m).

1.3 Although the metre is our standard length it is not convenient for measuring all lengths and other units are in common use. For lengths much smaller than ourselves we have: millimetres (mm); centimetres (cm); inches (in). For lengths similar in size to ourselves we use: metres (m); feet (ft); yards (yd). For modest distances, much bigger than ourselves, we user: kilometres (km); miles. For large distances we do not have new units but work with multiples of existing units: thousands of kilometres; millions of miles; etc. For astronomical distances we move to the strange units of: light years; parsecs, and for cosmological distances we have multiples: kiloparsecs (kpc); megaparsecs (Mpc).

1.4 We have lots of different units of length, all for measuring different sized intervals of the same scale - the length scale. We take it for granted that all these units are consistent with one another, that they all match up, and that we can readily convert from one to another.

1.5 In everyday use we are unaware that the length scale is involved in what we might think of as "non-length" quantities. We don't think of volume as length cubed when we buy a bottle of drink or fill up the car with petrol. We don't think of speed as length divided by time when we talk about how fast things move, and we certainly don't think of length when it comes to anything to do with energy. Somehow our brains have evolved to handle these quantities separately and we clearly function perfectly well with this separation.

1.6 The only time most of us are aware of the length scale is probably when we have to do some maths or physics homework problems where the units become important.

2 Local Variation of the Length Scale

2.1 If the length scale varied then would we notice or be able to tell? How would we detect any changes in the length scale?

2.2 Let us consider physical quantities that have units based on the scales of length, mass; and time, so all the quantities listed in Table 32.2. And let us also consider changes to just the length scale, so no changes to either the mass scale or the time scale. Now we can look at what happens when the length scale changes.

2.3 We do not measure absolute lengths, only relative lengths; that is lengths relative to some standard. Suppose we go to measure the width of our room as illustrated in Figure 14.1 above. We simply take our metre rule, measure the width, and note the value. We now double the length scale so that all lengths are twice as big. We re-measure the width of our room and find we get exactly the same value. How can that happen? Well the width of our room has actually doubled, it really is twice as big. The problem is that our ruler has also doubled in size. So when we measure the width we don't detect any change.

2.4 When the length scale changes all lengths change in proportion. So the ratio of the length of our ruler to the width of the room does not change, it remains exactly the same. This ratio is one length divided by another length; the length units cancel and we are left with a dimensionless number. The ratio has no units and the length scale is not part of it. This is the reason why we can never detect a change in the length scale at a local level.

2.5 If the length scale varies then all physical quantities that have length as part of their units change in proportion. So if the length doubles then areas increase by a factor of four (length squared), and volumes by a factor of eight (length cubed); speed and acceleration also double.

2.6 But, you may say, why don't we measure the distance using light instead and time how long it takes a photon to travel the distance. We measure the time taken and, as we know the speed of light, we can obtain the distance. But this fails as well. We can see this by examining the units. We know that distance is speed multiplied by time. So our distance is given by multiplying the speed of light by the time taken. But the units of the speed of light are length divided by time. So when we multiply the speed of light by the time taken the time units cancel out and we are left, as we must be, with just a length. What's happening under the bonnet is that the speed of light changes as well, in exactly the same proportion.

2.7 We are up against the barrier of our balanced physical equations, as discussed in section "6. Equations" of chapter "12: Measurements". The units on the left-hand side balance the units on the right-hand side exactly. Any change in the length scale affects all quantities involving length across the whole equation. They cancel out exactly.

2.8 If the length scale changed right across the Earth then we would not know. So, at a local level, the answer to the questions above is "No": there is no test we can carry out to detect a change in the length scale.

2.9 There is no evidence for any changes in the length scale on Earth or within the solar system. That is not to say that there aren't any changes but that if there are then they are smaller than one part in a billion.

2.10 Our only hope is to find a remote location where the length scale is different, and to find a physical equation where we are comparing a remote length there against a local length here.

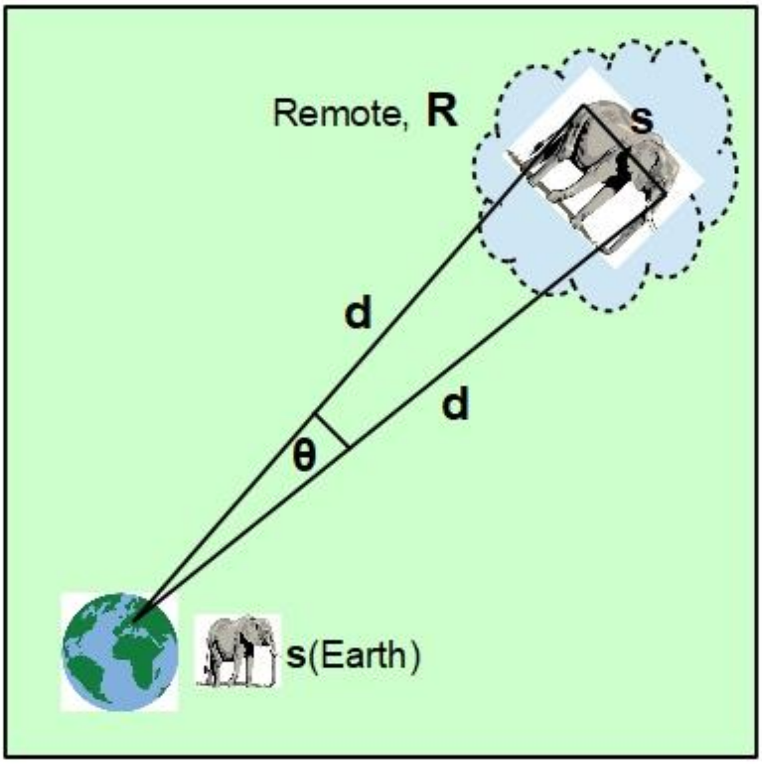

Figure 14.2. Measuring the size of a remote object using trigonometry.

3 Remote Variation of the Length Scale

3.1 Fortunately, when it comes to investigating possible changes in the length scale in remote locations, simple geometry comes to our rescue. Let's consider the situation illustrated in Figure 14.2 where we have two identical elephants, one on the Earth and the other on a remote planet.

3.2 We assume the length scale is the same everywhere in our Universe apart from in the remote region, $\boldsymbol{R}$. So we have the same length scale on Earth and in the space all the way to the remote region. This means the distance, $\boldsymbol{d}$, to the remote elephant is on the Earth's length scale; the fraction inside the remote region is taken to be insignificant.

3.3 We observe the second elephant in the remote region, $\boldsymbol{R}$, and measure its angular size, $\boldsymbol{\theta}$. The size of the elephant, $\boldsymbol{s}$, is then given by the simple relation

$$\boldsymbol{s} = \boldsymbol{d}\,\boldsymbol{\theta} \tag{14.1}$$

where $\boldsymbol{d}$ is the distance to the remote region; $\boldsymbol{\theta}$ is the angular size in radians.

3.4 We now compare the size of our elephant on Earth to the size we have calculated for the remote elephant. If they do not agree then we have no option but to conclude that the length scale in the remote region, $\boldsymbol{R}$, is different from here on Earth. Remember we have assumed the elephants are identical and there are no changes in the length scale except in the remote region.

3.5 This is just one method we could use to establish that the length scale in the remote region is different from Earth. There are many other methods to establish the same thing. It demonstrates that, in principle, we can detect changes in the length scale from location to location.

3.6 When we look at remote objects on an astronomical scale there is no evidence that the length scale changes. We can compare the apparent sizes of galaxies. Of course, galaxies come in all sorts of shapes and sizes, but when we compare similar galaxies there is no evidence that distant galaxies are any different from nearby ones.

3.7 The dark matter required to explain the missing mass in galaxies is more than five times the observed mass. Certainly the length scale in regions across the Universe does not change by this sort of number. Any changes that do occur must be miniscule, much less than one part in a million.

4 Cosmology

4.1 Physical cosmology tries to understand the Universe and one of the areas it covers is the expansion of the Universe.

4.2 The Friedmann equation describes the expansion of a homogeneous Universe in terms of a scale factor, a

$$\left(\frac{\dot{a}}{a}\right)^2 = H^2 = \frac{8\,\pi\,G}{3\,c^2}\,\varepsilon_c \tag{14.2}$$

where $\boldsymbol{a}$ is the length scale factor; $\dot{\boldsymbol{a}}$ the rate of change of the scale factor; $\boldsymbol{H}$ the Hubble parameter; $\boldsymbol{\varepsilon_c}$ the critical energy density.

4.3 If one object has a relative position of 0.2 and another 0.4 then at any later time when the Universe is much larger the two objects will still have positions 0.2 and 0.4 relative to one another.

4.4 The usual interpretation of the expansion of the Universe is that the distance between galaxies gets larger and larger, in accordance with the Friedmann equation. The galaxies themselves do not expand, just the space between them.

4.5 An alternative way of looking at it is that the length scale is shrinking and that our standard metre rule is getting smaller. From this point of view the galaxies are not moving at all. They only appear to be further apart because our measuring unit is shrinking and we can fit a greater number of them in.

4.6 This interpretation means we do have an example of the length scale varying, namely the expansion of the Universe.

5 Summary

5.1 Locally if the length scale varied there would no local effects and we would not be aware of any changes.

5.2 Remotely if the length scale varied then there are effects that we, here on Earth, could detect through observation of the remote location.

5.3 The cosmological length scale has changed with the expansion of the Universe.

5.4 There is no other evidence that the length scale varies anywhere or any time.

15

The Time Scale

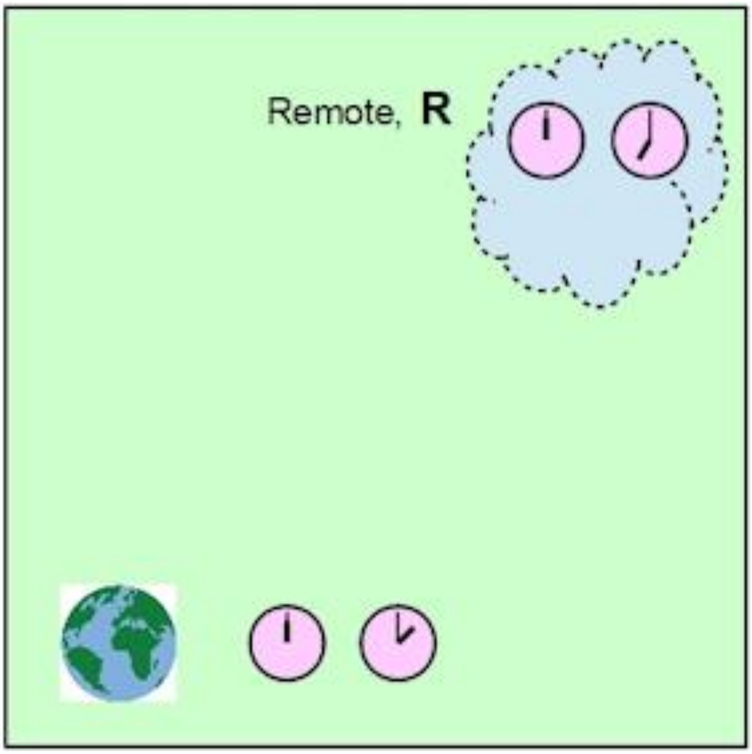

Figure 15.1. Measuring the time of a process by comparing clocks in a remote object with clocks on Earth.

We look at the time scale and ask the question "would we notice if the time scale varied?"

1 Time Scale

1.1 Time is our second basic scale. From Table 32.2 in chapter "32: Quantities and Units" we can see that time appears as one of the units in a number of common quantities. Time is present in: acceleration; angular momentum; energy; force; frequency; impulse; momentum; power; pressure; speed. Time is absent from: area; density; length; mass; volume. The quantities with time as one of their units all seem to be related with movement or change. The quantities without time all seem to be static.

1.2 The standard unit of time is the second (s).

1.3 We don't have the large range of different units for time that we have for length. Time is essentially measured using just seconds, hours, days, and years; together with subdivisions of seconds such as milliseconds or microseconds.

1.4 Time is a somewhat slippery concept to get hold of. We have an instinctive feeling for the passage of time and naturally associate time with change. Special relativity teaches us that space-time is four-dimensional, with time on an equal footing with space. However, it is a bit more difficult for us to grasp time as just another dimension similar to the three dimensions of space.

1.5 With space we are happy that we know where our house is and where the shops are. We accept it as perfectly normal that we can go to the shops and then back home again. We cannot do the same with time. We cannot go back to yesterday and then come back to today. Time does not allow us to do this. We can go back and forth in space but we cannot go back and forth in time.

1.6 We do not have the same relationship with time as we do with space. Somehow the past, the present, and the future are different. Also we cannot manipulate time in our heads in the same way we can with space. These difficulties are, or course, the result of how our human brain has evolved. The difficulties are in our heads and not out there in the real world.

1.7 Although we cannot go back and forth in time, there is nothing to stop mathematics and physics from doing so. They work quite happily with objects in space out to the edge of the Universe or in time all the way back to the end of inflation. As humans we operate in the now; the equations of mathematics and physics operate equally well at any time.

2 Local Variation of the Time Scale

2.1 If the time scale varied then would we be able to tell? How would we detect any changes in the time scale?

2.2 We can examine the consequences of a change in the time scale in the same way as we did for length. We consider physical quantities that have units based on the scales of length, mass; and time, so all the quantities listed in Table 32.2. And we consider changes to just the time scale, so no changes to either the mass scale or the length scale. Now we can look at what happens when the time scale changes.

2.3 We do not measure absolute times, only relative times; that is times relative to some standard. Suppose we have a one hour exam to take and to give ourselves a helping hand we halve the time scale. We think this should make our exam last two hours, more than enough time to guarantee that we pass. At the end of the exam we look at our paper and realise that we have completed exactly the same number of questions as before. And the clock on the wall shows that exactly one hour has elapsed. How can that happen? What we wanted was for everything else to slow down but for ourselves to remain on normal time. But when we slowed down the time scale everything slowed down. The thought processes in our brains slowed down; our hand-writing speed slowed down; the gear wheels in the clock slowed down. The time scale really did halve and everything really did slow down. But the effects all cancel out. However we attempt to measure the passage of time we won't be able to detect any change.

2.4 If the time scale varies then all physical quantities that have time as part of their units change in proportion. So if the time scale halves then speeds double (speed depends on inverse time), and accelerations double again (acceleration depends on the inverse of time squared).

2.5 This means that if the time scale changed right across the Earth then we would not know. So, at a local level, the answer to the questions above is "No": there is no test we could carry out to detect any change.

2.6 As with length we are up against the barrier of our balanced physical equation again. The units on the left-hand side balance the units on the right-hand side exactly. Any change in the time affects all quantities involving time across the whole equation. They cancel out exactly.

2.7 We do not observe any time variations on the Earth or indeed anywhere in the solar system. So either time variations do not happen or they only happen in more remote or exotic locations. The only hope is to find a remote location where the time scale is different, and to find a physical equation where we are comparing a remote time against a local time.

3 Remote Variation of the Time Scale

3.1 If the time scale has a different value in a remote region then we will observe the physics in that region to run either faster or slower. This variation affects all physical quantities that have time as one of their units. So speed, acceleration, frequency, energy, force, power, impulse, etc, are all affected.

3.2 We can imagine a remote region where time runs 7 times faster than here. Of course, as discussed in section 2 above, in the region itself local observers see everything progressing at normal pace. They are not aware of any changes at all.

3.3 For us on Earth a caesium wall clock in the remote region appears to run 7 times quicker. So if our local caesium clock is synchronised with the remote caesium clock at midnight then when our clock show 1:00am we observe the remote clock to show 7:00am (say). This is illustrated in Figure 15.1.

3.4 It may, of course, be difficult to find a remote caesium clock but other standard physical processes may be detected, such as the radioactive decay of elements in a supernova explosion. A hot star with a lifetime of 70 million years will, from our point of view, exhaust its fuel after just 10 million years and then explode as a supernova.

3.5 Another way is to measure light travel times. If the time scale changes then so does the speed of light, as do all velocities. We may be lucky enough to have a supernova in the remote region in which case we should be able to observe the time delay as regions distant from the supernova get illuminated by radiation.

3.6 We need to be careful when dealing with photons. At first sight when the time scale changes then so do the frequencies of photons. So we might think we can detect this when the photons arrive at the Earth. If time scale is halved then the frequencies in the remote region are doubled. However, when the photons reach Earth they have exactly the same frequency as similar photons produced here. The easiest way of seeing this is by noting that the photon's wavelength has not changed (we've only changed the time scale) and our local speed of light has not changed. When the photon arrives it has the same wavelength and speed as local photons. So the frequency is also exactly that of our local photon. A Lyman alpha photon emanating from the remote region will be identical to a Lyman alpha photon created on Earth. I know, this is really counterintuitive.

4 Type Ia Supernovae

4.1 Type Ia supernovae are thought to be white dwarf stars that accrete matter from a close companion and eventually go over the Chandrasekhar limit of around 1.4 solar masses. At that point they explode and the white dwarf is destroyed.

4.2 The physical set up is more or less identical for all type Ia supernovae and so they can be used as standard candles to measure the distance of remote objects. However, observations show that the light curves are not all the same; some decay quickly whereas others decay slowly.

4.3 The light curves can be made the same by applying a stretch to the time scale. The standard curve used for stretching type Ia supernovae is known as the Phillips curve. Whenever a supernova is observed its light curve is stretched to match the Phillips curve before being used as a standard candle. The reason for the differences in the light curve is not fully understood.

4.4 The stretching of the light curve is clearly a stretching of the time scale. So this may be a case of a region of space where the time scale is different from here on Earth.

5 Summary

5.1 Locally if the time scale varies there are no local effects and we are not be aware of any changes.

5.2 Remotely if the time scale varies then there are effects that we, here on Earth, could detect through observations of the remote location. No such effects have been detected.

5.3 There is a suggestion that changes in the time scale might explain the light curves of type Ia supernovae.

5.4 There is no other evidence that the time scale varies anywhere or any time.

16

The Energy Scale

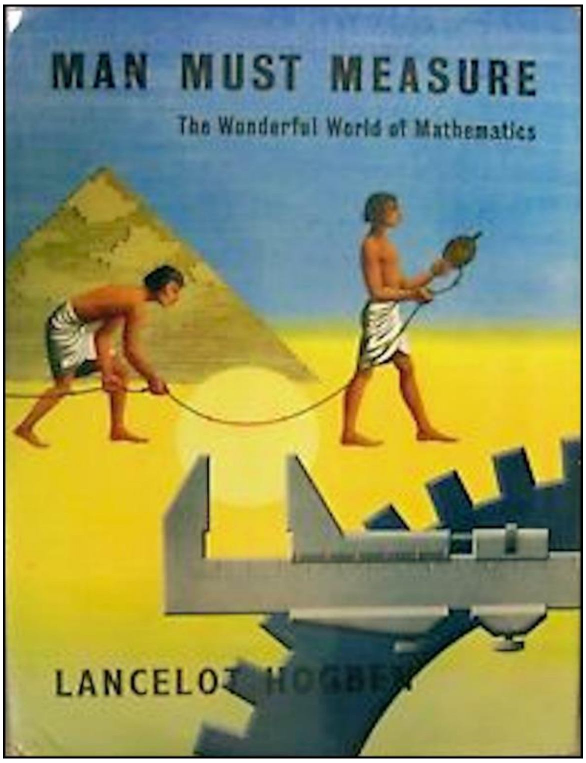

Figure 16.1. Cover of "Man Must Measure", the book by Lancelot Hogben that got me interested in science all those years ago.

We look at the energy scale and ask the question "what happens when the energy scale changes?"

1 The Switch from Mass to Energy

1.1 In this chapter we finally come to discussing the energy scale and variations of the energy scale. Up to now we have been working with the scales of length, time, and mass. We've already looked at length and time, so you probably expected us to look at mass next. But for explaining away dark matter we need to move from the mass scale to the energy scale. We start by looking at why this switch is necessary.

1.2 Special relativity shows that mass, $\boldsymbol{m}$, is just one form of energy, $\boldsymbol{E}$, and we are all familiar with Einstein's equation

$$\boldsymbol{E} = \boldsymbol{m}\,\boldsymbol{c}^2 \tag{16.1}$$

where $\boldsymbol{c}$ is the speed of light. So if we have a mass we can easily get to energy by multiplying by the square of the speed of light.

1.3 We also know that photons (and other particles that move at the speed of light) have no mass but they do have energy as given by

$$\boldsymbol{E} = \boldsymbol{h}\,\boldsymbol{\nu} \tag{16.2}$$

where $\boldsymbol{h}$ is Planck's constant; $\boldsymbol{\nu}$ is the frequency. So in switching to energy we can work with matter (mass) and radiation (photons) at the same time. We don't have the awkward problem of excluding radiation whenever we're working with mass.

1.4 We are probably familiar that momentum is just mass times velocity. Photons also have momentum, p , given by

$$\boldsymbol{p} = \boldsymbol{E} / \boldsymbol{c} \tag{16.3}$$

1.5 So both matter and radiation have momentum. They can be pushed around equally well (i.e. have their momentum changed) by being hit by another mass (collision) or by being bombarded by photons (radiation pressure).

1.6 If we look at Table "32.2: Common Quantities" in chapter "32: Quantities and Units" we can see that many quantities have simpler units using the ELT system (energy length time) compared to the usual MLT system (mass length time). An example is energy itself; in the MLT system energy has units of M L^2 T^{-2}, whereas in the ELT system it is just E. An exception is the gravitation constant (Table 32.3 Fundamental Constants) which is pretty complicated in both systems.

1.7 General relativity, our best theory for gravity, shows that gravity is a consequence of the curvature of space-time. The curvature of space-time is determined by the energy-momentum tensor, which is a complex mathematical object with multiple components constructed from energy and momentum. So moving from the mass scale to the energy scale helps here as well.

1.8 The bottom line is that all forms of energy contribute to the gravitational force, not just mass. Mass is just one form of energy and this is not good enough when working with gravity. So, as we are dealing with gravity throughout this book, it is better to work with energy rather than mass and to switch from the mass scale to a scale based on energy.

2 Energy Scale

2.1 We start with some thoughts on working with energy. Next we look at the implications of local variations in the energy scale on Earth. Then we move to variations in remote locations and how we might recognise them.

2.2 We are commonly aware of energy in three ways.

2.3 Firstly our fuel bills. We may not be aware of how much energy we consume in our homes but we are certainly aware of how much we pay for it. In the UK we are charged for the number of kilowatt hours (kWh) we consume. It is odd that we are not charged by a unit of energy (joules) but by a unit of power (kilowatts) multiplied by a unit of time (hours). But that is OK as energy is power times time.

2.4 Secondly our cars. In the UK we worry about the price of the petrol we burn in terms of miles per gallon. This is even odder as we have a unit of distance divided by a unit of volume, ending up with an inverse area!

2.5 Thirdly the food we eat. In the UK we are constantly bombarded with how many calories we are consuming. Unit-wise food gets it right: the calorie (cal) is a unit of energy; one calorie is about 4.2 joules. But when we talk about calories in food we invariably mean kilocalories (kcal) or a thousand calories. Next time you look at the nutritional values of a food item you will notice the units are kilojoules (kJ) or kilocalories (kcal).

2.6 We are all aware of Einstein's relation between mass, m, and energy, E, as given in equation (16.1) above. If we are trying to lose weight we should be aware that one pound of fat is equivalent to around four thousand (kilo) calories of energy. This is a different relation between mass (weight) and energy. 4,000 calories is roughly what a woman eats in two days or a man in a day and a half. So if you want to lose a pound of fat you know what you have to do.

2.7 From Table 32.2 in chapter "32: Quantities and Units" we can see that energy is present in: angular momentum; density; force; impulse; mass; momentum; power; pressure. Energy is absent from: acceleration; frequency; length; speed; time; volume.

2.8 The standard unit of energy is the joule (J).

3 Local Variation of the energy Scale

3.1 If the energy scale varied then would we be able to tell? How would we detect any changes in the energy scale?

3.2 We consider measurements where the scales are: energy; length; time. And we consider changes to just the energy scale; there are no changes to either the length scale or the time scale. So there are no change to speeds either, including the speed of light.

3.3 We do not have any simple pieces of equipment for measuring energy. This is unlike length and time where we have rulers and clocks. However, we can start by working indirectly with weight rather than directly with energy. For this we have balances or weighing scales.

3.4 If the energy scale changes across the whole Earth then we will not notice. Our pair of scales continues to measure weights exactly as before. A pound of potatoes on our scales still shows a weight of one pound. Whatever we put on one side of the scales is balanced by our weights on the other side.

3.5 What about a spring balance where the weight is measured by the extension of a spring. Here we weigh an item by measuring the length of a spring. We started by assuming no change to the length scale and our length unit does not contain energy. So the spring balance gives exactly the same weight. This works because Young's modulus for the spring has energy as part of its units. So when the energy scale changes so does Young's modulus. Similar arguments apply for electronic scales.

3.6 Going back to energy, won't our electricity meters give different readings? When we boil an electric kettle of water it takes the same amount of energy as before. The way temperature relates to energy is defined by the specific heat of the substance. But the units of specific heat contain energy. So if the energy scale changes then so do the specific heats and, again we detect no change in the amount of electricity we consume.

3.7 When we put energy into substances they get hot. Are there detectable changes in our temperature measurements? In physics temperature is related to energy through the use of Boltzmann's constant. However, Boltzmann's constant contains the units of energy and this again cancels out any changes. So if the energy scale changes we don't observe any differences in our temperature measurements.

3.8 With light, the relation between the energy of a photon and its frequency or wavelength is defined by Planck's constant. Again the units of Planck's constant contain the units of energy. We observe no differences.

3.9 In practice we do not observe any energy variations on the Earth or indeed anywhere in the solar system. So either energy variations do not happen or they only happen in more remote or exotic locations. The only hope is to find a remote location where the energy scale is different, and to find a physical equation where we are comparing a remote energy against a local energy.

4 Remote Variation of the Energy Scale

4.1 If the energy scale in a remote region is different from here on Earth then, from what has been said above, observers in the remote region do not notice anything different. If they carry out experiments locally and transmit the results to us we do not see any differences either.

4.2 What about photons emitted by a known process, with a known energy (e.g. the Lyman-alpha line of atomic hydrogen). Sure, the photon in the remote region has a different energy from here. But we are not measuring the photon in the remote region. We have assumed that only the energy scale changes; no changes to lengths or times. So, when the photon arrives, it has the same wavelength and the same frequency as that expected for a Lyman-alpha photon here on Earth. For any process in the remote region the energy of photons arriving here will be in exact agreement with the energy of a local photon emitted by the same process on Earth.

4.3 Local observers cannot detect anything and remote observers can't detect anything either. We seem to be at an impasse. The only way out is to find an experiment that involves energy quantities in both regions. And that is exactly what gravity does for us.

5 Gravity

5.1 Newton's law of gravity for the force between two masses is

$$\boldsymbol{F} = \frac{\boldsymbol{G\, m_1\, m_2}}{\boldsymbol{r^2}} \tag{16.4}$$

where $\boldsymbol{F}$ is the force; $\boldsymbol{m_1}$, $\boldsymbol{m_2}$ the two masses; $\boldsymbol{r}$ the distance between them.
This tells us that the gravitational force depends on the product of the masses and on the inverse square of the distance. One of the masses is local and the other is remote.

5.2 This is different from light where the photons we observe are observed on Earth and not in the remote region. With gravity the remote mass is still in the remote region and so behaves with the energy scale there and not the energy scale here.

5.3 The gravitational pull on the Earth, keeping it in its orbit around the Sun, depends on the value of the Sun's mass at the Earth; i.e. the value of the mass of the Sun as measured by an observer on Earth. There is no suggestion that the energy scale varies across the solar system. In fact, the strict adherence of the planets to Kepler's third law (period squared proportional to distance cubed) demonstrates conclusively that the energy scale is fixed.

5.4 Nevertheless, if the energy scale changed within the Earth, but was constant outside and on the surface, we would not know. And, similarly, we could not detect a change in the energy scale within the Sun.

6 Summary

6.1 Locally if the energy scale varies there are no local effects and we cannot be aware of any changes.

6.2 Remotely if the energy scale varies there then there are no effects within the remote location and remote observers cannot detect any effects.

6.3 When we on Earth observe phenomena in the remote location we also detect no changes.

6.4 The only detectable effect of a difference in the energy scale is when both locations are involved and this means with gravity. This is because we have a mass in one location acting on another mass in a different location, i.e. action at a distance.

6.5 In the next chapter we see how gravity and a variation in the energy scale work together to give rise to effects we can detect.

17

How It Works

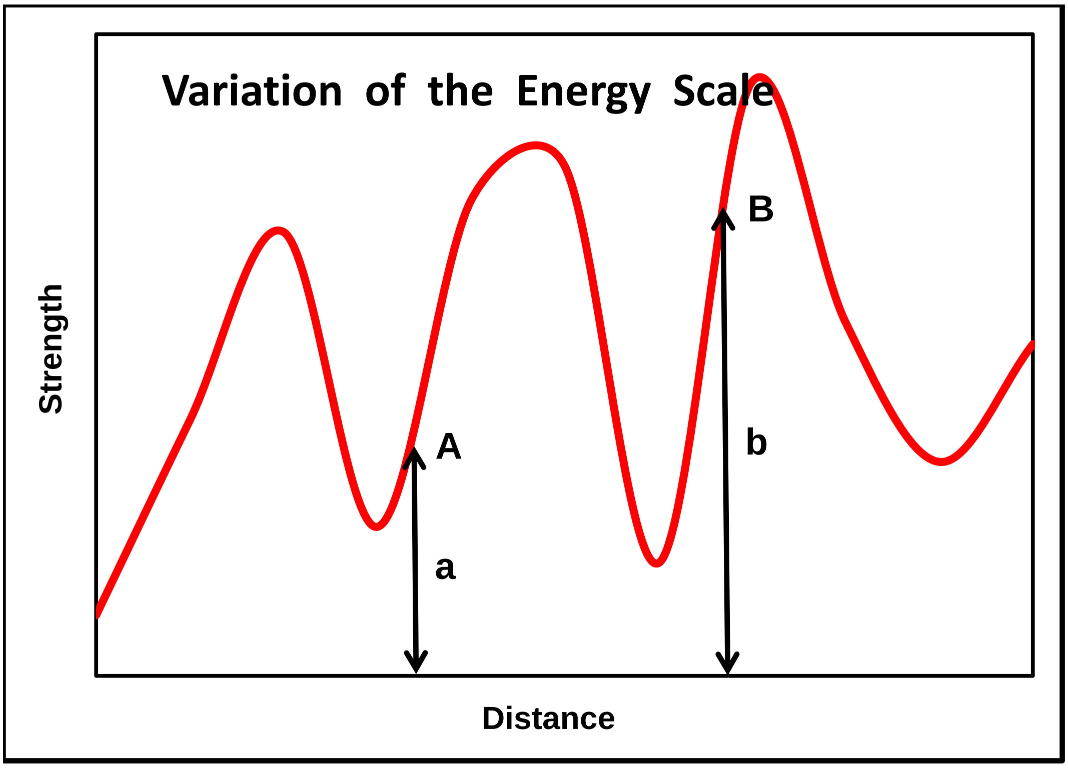

Figure 17.1. Illustration of the way the energy scale might vary from place to place.

We look at energy scale variations and answer the question "how does an energy scale variation change the way gravity works?"

1 Variations of the Energy Scale

1.1 We are comfortable with the notion of temperature and that different places have different temperatures. So for example Singapore is generally hotter than Berlin and has a higher temperature. We should also be comfortable in assigning a value of temperature, T, at every point in space. So Singapore might be at 35C and Berlin at 16C.

1.2 We do exactly the same with the energy scale. We introduce the parameter, ξ, that measures the strength of the energy scale and assign a ξ value to every point in space.

1.3 This is illustrated in Figure 17.1 where the red curve represents the strength of the energy scale and how it can vary from location to location. For an observer at A the energy at B appears to have a value scaled by b/a, in this case an increase. Similarly for an observer at B the energy at A appears to have a value scaled by a/b, in this case a decrease.

1.4 It is the ratio of the strengths of the energy scale at the two locations that is used, and not the difference between them.

2 Gravitational Attraction

2.1 We can look at how this works for the gravitational attraction between two masses. The situation is illustrated in Figure 17.2 where we have a large mass, M, at location A and a small mass, m, at location B.

2.2 The gravitational force, F, between the masses as given by Newton's law of gravitation depends on the product of the masses and inversely on the square of the distance. The equation for this is

$$F = -\frac{G\,M\,m}{r^2} = -F_A = F_B \tag{17.1}$$

The equation is symmetric in the sense that the magnitude of the force on mass M at A, F_A, is exactly the same as the force on mass m at B, F_B. There is, of course, a difference in sign as the forces act in opposite directions.

2.3 We now look at how this changes to take into account the energy scale variation. We start at location A where large mass, M, is and where the energy scale has the value a. The value of the energy scale for the smaller mass, m, at location B is b. Applying what we said in paragraph 1.4 the gravitational force at A is our basic Newtonian force multiplied by the ratio of b over a. The equation for this is simply

$$F_A = \frac{G\,M\,m}{r^2}\left\{\frac{b}{a}\right\} \tag{17.2}$$

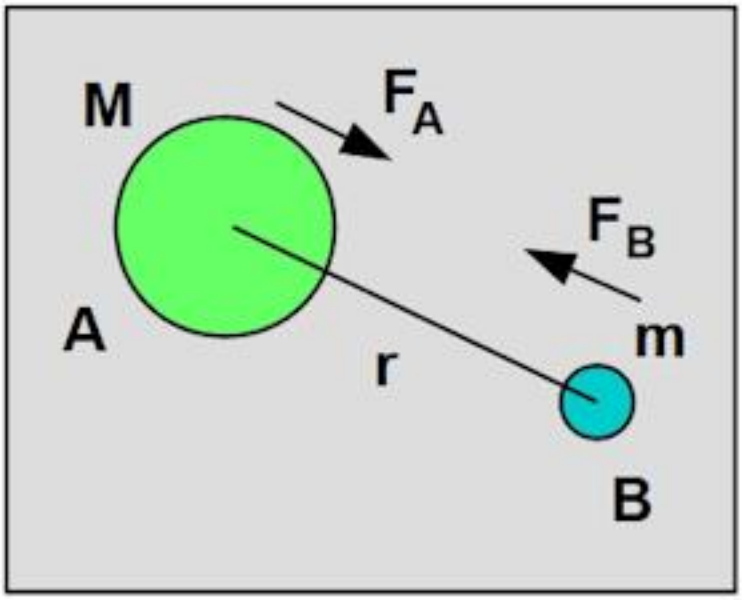

Figure 17.2. Illustration of gravitational force between two masses.

2.4 Similarly the gravitational force at $\boldsymbol{B}$ is our basic Newtonian force multiplied by the ratio $\boldsymbol{a}$ over $\boldsymbol{b}$. The equation for this is

$$\boldsymbol{F_B} = -\frac{\boldsymbol{G\,M\,m}}{\boldsymbol{r^2}}\left\{\frac{\boldsymbol{a}}{\boldsymbol{b}}\right\} \tag{17.3}$$

2.5 Our new equations differ from basic Newtonian gravity simply because the two masses are at separate locations and because the energy scale has different values at those two locations. At $\boldsymbol{A}$ the Newtonian force gets multiplied by $\boldsymbol{b}$ over $\boldsymbol{a}$, and at $\boldsymbol{B}$ it gets multiplied by the inverse ratio, $\boldsymbol{a}$ over $\boldsymbol{b}$.

2.6 On the Earth and across the solar system there appear to be no variations in the energy scale. So in nearby space the ratios of $\{\boldsymbol{b/a}\}$ and $\{\boldsymbol{a/b}\}$ are the same and both equal to 1, and we are back with the normal Newtonian gravity as given by equation (17.1).

2.7 One consequence, that you may have noticed, is that we have broken Newton's third law and action and reaction are no longer equal and opposite. Instead of

$$\boldsymbol{F_A} = \boldsymbol{F_B} \tag{17.4}$$

we have the relation

$$\boldsymbol{F_A\,a} = \boldsymbol{F_B\,b} \tag{17.5}$$

We get back to Newton's law if the masses are sufficiently close to one another that the strengths of the energy scale variation are essentially identical. As $\boldsymbol{A}$ and $\boldsymbol{B}$ approach one another the values of the energy scale become the same.
(Technical note: the above relation also takes into account that there is a similar inverse relation for the gravitational constant, $\boldsymbol{G}$, between the two locations).

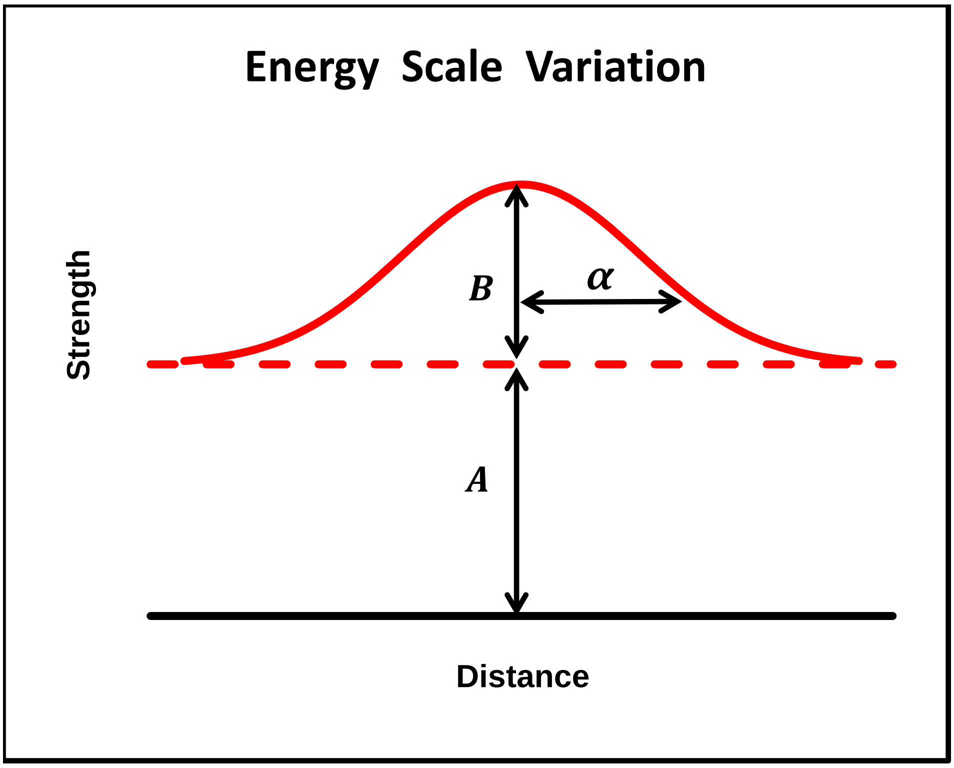

*Figure 17.3. Illustration of a Gaussian-shaped energy scale variation. The dashed red line is the background level with a height of **A**. The solid red curve is the Gaussian distribution with a central height, **B**, above the background. The Gaussian is also characterised by its width, **α**.*

3 The Shape of an Energy Scale Variation

3.1 We do not know the shape of an energy scale variation. In Figure 17.1 we showed a smooth random variation of the energy scale but we need a shape for an individual variation.

3.2 Many physical quantities seem to have a Gaussian distribution of fluctuations superposed on top of an average level. For example: if we have a hot liquid then it has an average temperature but some cells are hotter and other cells cooler. If we look at departures from the average then a lot of cells are slightly hotter or slightly cooler, but only a few are much hotter or much cooler. This peaked distribution is exactly what the Gaussian distribution gives us.

3.3 For the astronomical phenomena we have looked at in this book we need a shape for a single energy scale variation. So, following what was said above, we choose a Gaussian profile for the variation sitting on top of a background level. This is illustrated in Figure 17.3. The dashed red line is the background level. The solid red curve is the Gaussian energy scale variation.

3.4 The Gaussian shape has a number of properties that we need to be aware of. It is fully specified by just two parameters: the height, $\boldsymbol{B}$; the width, $\boldsymbol{\alpha}$. We also need a third parameter, the height of the background level, $\boldsymbol{A}$. At its middle the Gaussian is flat; this means there is little change in the value close to the middle. And finally, away from the middle the value drops quickly to the background level.

3.5 When we come to galaxy rotation curves we assume the spiral galaxy is centred on a large Gaussian energy scale variation that covers the whole galaxy. And for clusters of galaxies we again assume the entire cluster is embedded in a large Gaussian energy scale variation comparable in size to the cluster.

3.6 There is no reason why the energy scale variations have to have a positive strength as illustrated in Figure 17.3. We presume the variations come with a random distribution of heights and widths. Energy scale variations that lie below the background level should occur just as frequently. These are regions where the gravitational effects are diminished. Such regions will naturally lose matter to regions with a more positive strength and so, on a cosmic scale, will end up as voids.

4 Gravitational Force

4.1 We can see how the gravitational force is changed for a mass lying inside an energy scale variation. Rather than work with a point mass, which is somewhat unrealistic, we work with a narrow Gaussian density distribution. The density is highest at the centre and drops off towards the edge; this is more realistic of a spiral galaxy. For the energy scale variation we choose a much broader Gaussian that embraces the whole galaxy.

4.2 This situation is illustrated in Figure 17.4. The brown curve is the density distribution of the matter. It is a narrow Gaussian and the density falls rapidly towards zero as we go away from the centre. The red curve is the distribution of the energy scale variation. It is a broad Gaussian and decreases away from the centre to the constant background level shown by the dashed red line. Unlike the density distribution the energy scale never goes to zero.

4.3 Figure 17.5 shows the gravitational force arising from the Figure 17.4. The dashed green curve is the gravitational force for normal Newtonian gravity, as given by equation 17.1. It looks similar to the Gaussian curves in Figure 17.4 but its decline is much slower. The solid red curve is the gravitational force for the energy scale variation. The strength at the centre is exactly the same as for Newtonian gravity. But as we go away from the centre the force decreases less rapidly. At the half way point the strength is almost double that of Newtonian gravity, and by the outer limit it is over three times stronger.

4.4 Figure 17.5 clearly shows how energy scale variations work. Close to the centre the energy scale variation has little effect and normal Newtonian gravity applies. Away from the centre the energy scale variation has a bigger influence and the central mass behaves as if it is much greater than is actually the case. The energy scale variation has the same effect as the addition of large amounts of dark matter. All those scenarios where the existence of dark matter is invoked can equally well be explained using a variation in the energy scale.

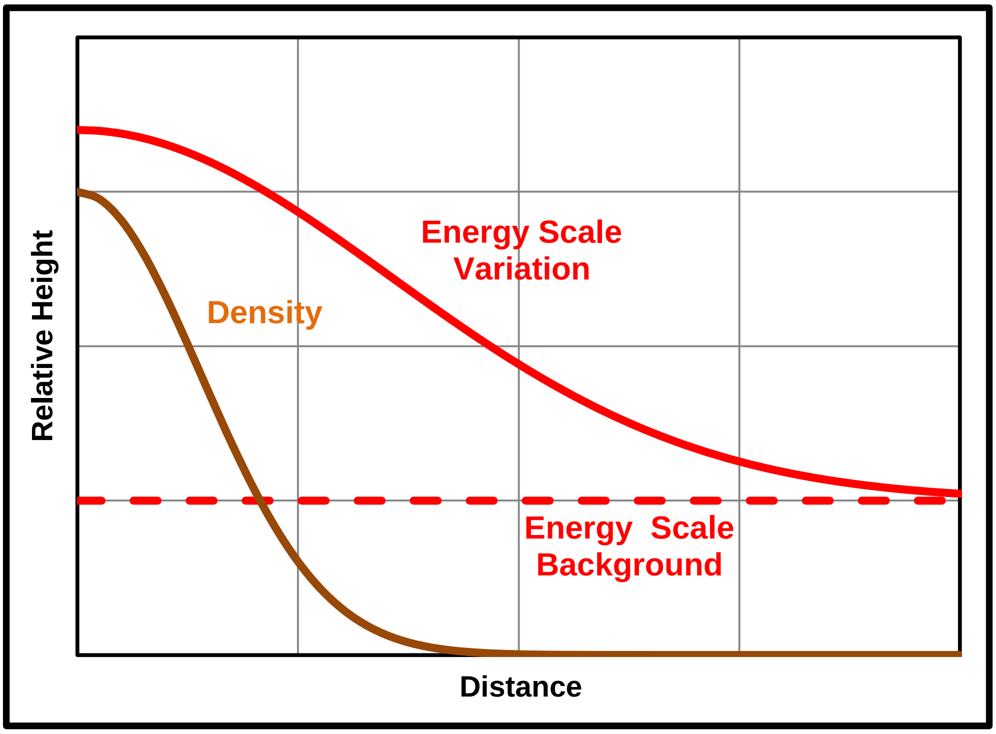

Figure 17.4. Illustration of the set-up for an energy scale variation. The solid brown curve shows the narrow Gaussian-shaped density distribution. The solid red curve shows the broad Gaussian-shaped energy scale variation. The dashed red curve is the background level of the energy scale.

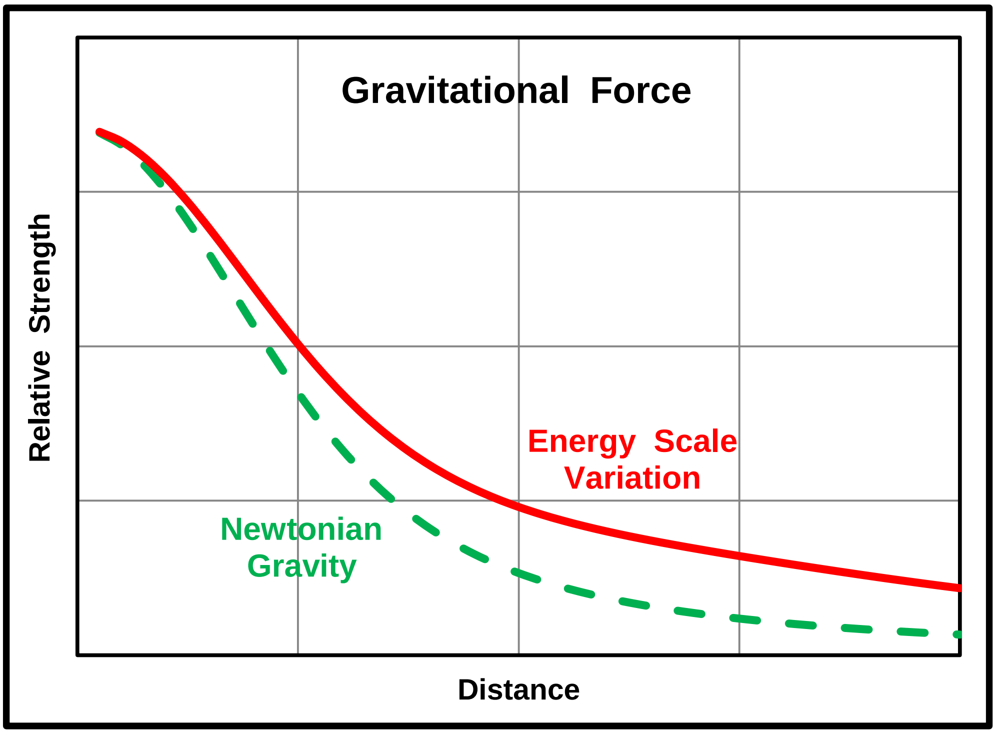

Figure 17.5. Illustration showing the gravitational force arising from Figure 17.4. The dashed green curve is the relative force for Newtonian gravity. The solid red curve is the relative force for the energy scale variation.

5 Multiply; Don't Add

5.1 The following example may help to clarify how what we are doing with variations of the energy scale compares with dark matter.

5.2 We have 4 widgets and we need 24 widgets. How do we get from 4 to 24?

5.3 The Dark Matter Way
We haven't got the same widgets so we add in 20 alternate widgets that do the same thing:

$$4 + 20 = 24$$

Normal matter on its own cannot explain many observations involving gravity. The gravitational force needs to be around 6 times stronger. So we add in 5 times as much dark matter as normal matter. We get the gravitational force we need. Job done.

5.4 The Energy Scale Variation Way
We multiply the influence of every widget by a factor of 6:

$$4 \times 6 = 24$$

If the energy scale at the location of the source is 6 times stronger than at the location of the target then the gravitational force is 6 times stronger than expected. We do not have to introduce a new particle, in the form of dark matter, in order to get the gravitational force we need. We simply change the strength of the energy scale. Job done.

5.5 We don't add; we multiply; job done. This simple idea is all we need to explain those situations where dark matter is invoked. Those situations were described in the previous chapters.

6 Only the Energy Scale

6.1 We should be aware of a technical reason for ruling out variations in either the length scale or the time scale. This reason arises because there is a full mathematical theory behind all of physics and much of this is based on calculus with the use of differentiation and integration.

6.2 The theory of systems in equilibrium is covered by statics and this looks at how forces and other physical quantities change with position. For example we are aware that atmospheric pressure changes with height, and the lifting power of a lever depends on its length. Changes with respect to distance are handled using differential calculus where we are differentiating with respect to distance. We are clearly in trouble if our length scale is varying while at the same time we are trying to measure lengths. It is a problem knowing how to differentiate with respect to distance when our distance (length) scale is changing. We can avoid this problem entirely if we assume that the length scale is fixed, and that is exactly what we are doing here.

6.3 The theory of how things move is covered by dynamics and this looks at how position, speed, and acceleration change with time. For example we are all aware that speed is the change of distance with time, and that acceleration is the change of speed with time. Changes with respect to time involve differential calculus where we are differentiating with respect to time. Again we are in trouble if we are trying to explain how systems change with time if our underlying time scale is varying. We can avoid this problem if we assume that the time scale if fixed, and as with length that is exactly what we are doing here.

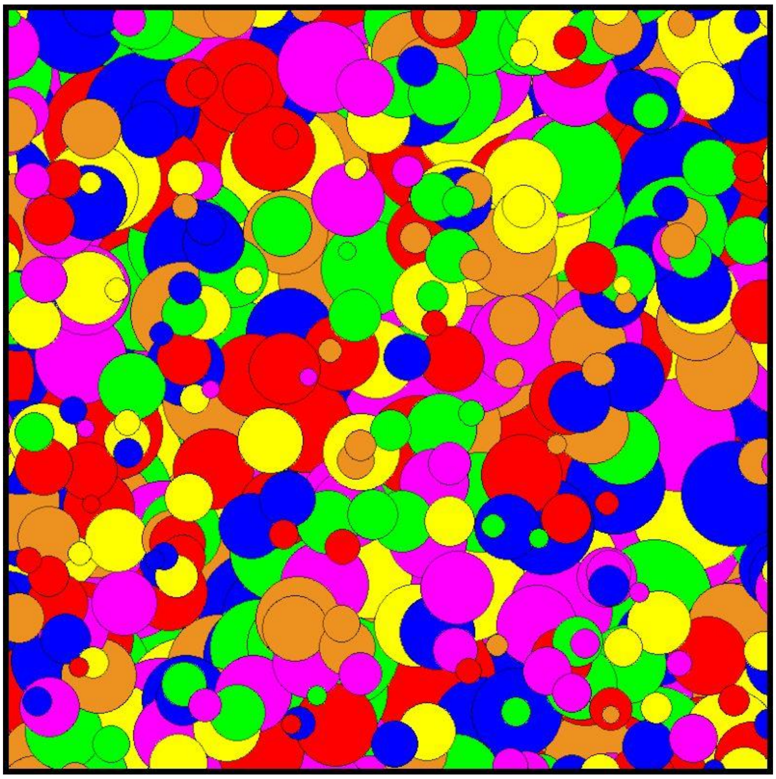

Figure 17.6. Illustration of a random distribution of energy scale variations.

7 Illustration

7.1 Figure 17.6 illustrates, in two-dimensions, the nature of variations of the energy scale. It shows a random distribution of circles of different colours and different sizes. The size of each circle indicates the width of the energy scale variation. We can imagine the strength goes from red the strongest, through orange, yellow, green, blue, to purple the weakest.

7.2 Although the distribution is random we still get areas where one colour dominates. We might expect regions that are predominantly strong to evolve into clusters of galaxies, and regions that are predominantly weak to evolve into cosmic voids.

8 An Analogy

8.1 Hopefully the following analogy will go some way to explaining how a variation in the energy scale can change the way gravity works.

8.2 Imagine two identical houses; exactly the same construction, exactly the same contents.
The first house is located in New York and is valued at $20 million.
The second house is located in Detroit and is valued at $2 million.

8.3 Both house owners buy shares in a profitable company backed by the value of their houses.
The first owner buys shares worth $20 million and makes a profit of $10 million.
The second owner can only buy shares worth $2 million and so makes a profile of just $1 million.

8.4 The houses haven't changed; they are still exactly the same. And yet one generates a profit ten times greater than the other. The only difference is the location of the property.

8.5 Back to energy scale variations. We can have identical masses in different locations where the values of the energy scale are different. The effect of one mass can be much larger than the effect of the other. This is exactly the way that variations in the energy scale can do away with dark matter and explain all the observations where dark matter is invoked.

9 Summary

9.1 An energy scale variation centred on a massive object means the gravitational attraction on objects further out can be enhanced by a large factor.

9.2 There is little effect on nearby objects and for close objects normal Newtonian gravity applies. Thus no effects are expected to be detectable across the solar system, and no effects in the central regions of galaxies.

9.3 In the early chapters we looked at those astronomical situations where the existence of dark matter is required. In the following chapters we revisit those same situations and see how energy scale variations can replace dark matter.

18

Galaxy Rotation Curves

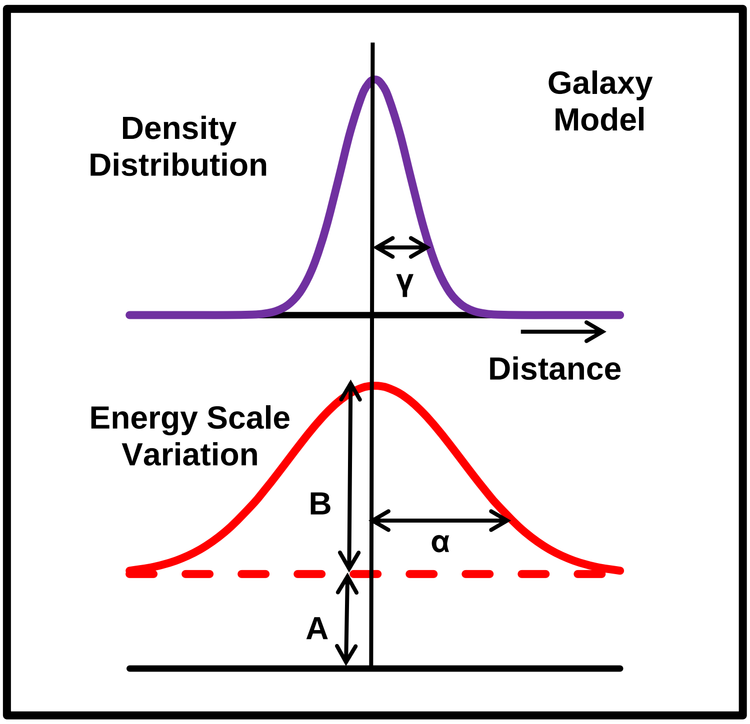

Figure 18.1. Model of a spiral galaxy. The upper purple curve shows the narrow Gaussian shape of the density distribution. The lower red curve shows the broad Gaussian shape of the energy scale variation, which sits on top of a background level shown as the red dashed line.

We revisit chapter "4: Galaxy Rotation Curves", and answer the question "how does our new idea explain everything that dark matter explains?"

1 The Energy Scale Variation Solution

1.1 Spiral galaxies are observed to have flat rotation curves in their outer regions. This is not what is expected from Newtonian gravitation. The currently accepted explanation is that every galaxy is embedded in a large halo of dark matter and this provides the extra mass required to produce the high rotation speed.

1.2 In this chapter we look at how energy scale variations give rise to flat rotation curves and the high rotation speeds. We need a simple model for a galaxy and a simple model for an energy scale variation. We then see how the two fit together to produce a flat rotation curve.

1.3 We model a galaxy as a thick disk with a Gaussian density distribution. This is illustrated in the upper part of Figure 18.1 where the thick purple line represents the density distribution. It has a central peak and an exponential fall off towards the outer regions So, most of the mass is concentrated in the galaxy centre, just as observed in real galaxies. Spiral galaxies come in all sorts of shapes and sizes. So the width of the Gaussian has to be an adjustable parameter that varies from galaxy to galaxy and caters for galaxies of different sizes and masses. The Gaussian shape means the density falls off rapidly to zero and this imposes a practical limit on the size of the galaxy and gives it a more or less definite edge.

1.4 We model the energy scale variation as another Gaussian with its maximum at the galaxy centre and dropping off exponentially to the outer edges. This is illustrated in the lower part of Figure 18.1 where the thick red line represents the variation in the energy scale. The height and width of the Gaussian are left as adjustable parameters to allow us to fit different galaxies. The background level of the energy scale is illustrated as the red dashed line. The Gaussian sits on top of this fixed background level and the variation drops to this constant value at large distances. Unlike the density, the variation in the energy scale does not drop to zero.

1.5 We can now use our model to generate rotation curves and compare these with real galaxies. The Gaussian for the density distribution is always quite narrow with a width of around 8 kpc. For comparison this is the distance of our sun from the galactic centre. The Gaussian for the energy scale variation is always much broader with a width of around 20 kpc. The difference in the widths is also illustrated in Figure 18.1.

1.6 Figure 18.2 shows the different rotation curves that arise when the strength of the energy scale variation is allowed to change, while keeping the density distribution fixed. The green dashed curve at the bottom is for pure Newtonian gravitation, i.e. for no energy scale variation. The figure shows that changing the strength of the energy scale variation produces large changes to the outer regions but hardly any changes near the galaxy centre.

1.7 All the curves lie above the curve for Newtonian gravity. This means the rotation velocities are always higher and the stars are always moving faster than expected. The curves show a range of shapes; they are not all flat. The red curve and the curve below have the flattest shapes in their middle parts. These are the curves that would match those spiral galaxies that have flattish rotation curves. Towards the outer limits all the curves begin to show a fall off. This fall off is always parallel to the Newtonian fall off but at a higher level.

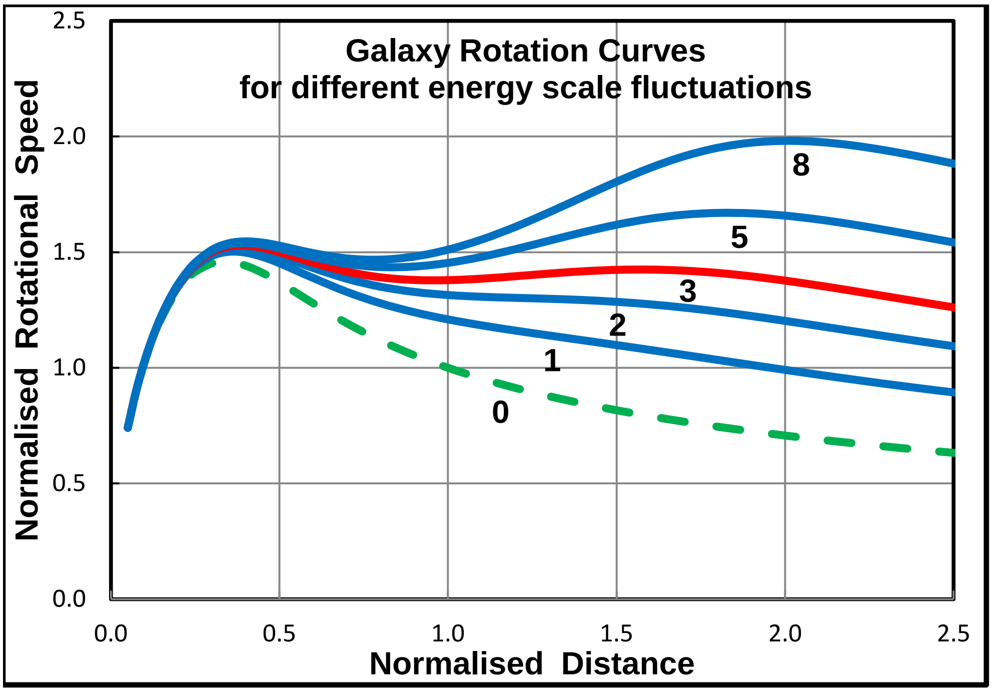

Figure 18.2. Illustration showing how the shape of the rotation curve changes when the strength of the energy scale variation changes. The green dashed curve is Newtonian gravitation. The red curve is the same as in Figure 18.3.

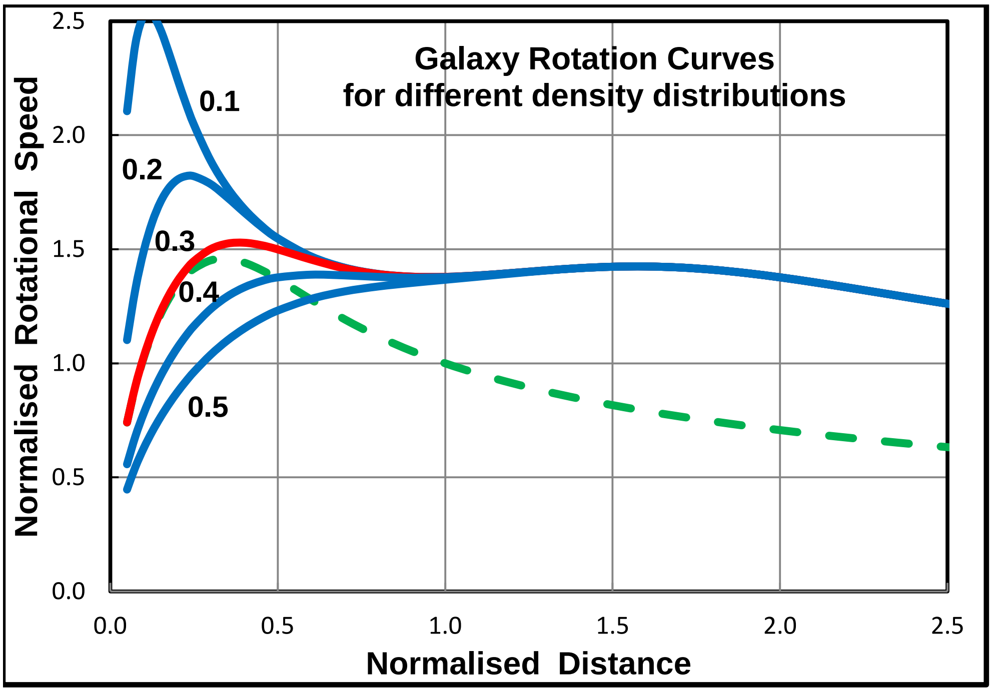

Figure 18.3. Illustration showing how the shape of the rotation curve changes when the width of the density distribution changes. The green dashed curve is Newtonian gravitation. The red curve is the same as in Figure 18.2.

1.8 Figure 18.3 shows the different rotation curves that arise when the density distribution is changed but the energy scale variation is kept fixed. Again the green dashed curve is for Newtonian gravitation with no energy scale variation present. The key point from this figure is that there are large changes in the inner regions of the galaxy centre but hardly any changes in the outer regions.

1.9 Figures 18.2 and 18.3 do not show the full range of possible rotation curves. Figure 18.2 shows the different curves that arise for one given density distribution. Figure 18.3 show the curves for one given variation of the energy scale. The two figures should give you a good idea of the kinds of rotation curves that can arise.

1.10 The rotation curves of spiral galaxies are often called 'flat'. It is clear from Figures 18.2 and 18.3 that the rotation curves that arise from variations in the energy scale are in general not flat. They show a range of different shapes and only a few have a flattish region in the middle area.

1.11 We have four free parameters for fitting the model to the observations: two for the density and two for the energy scale variation.

(a) a parameter that defines the central density. The effect of this parameter is to move the curve vertically up or down so that rotation speeds are at the right level. This parameter also gives us an estimate of the total mass of the galaxy.
(b) The 1/e-width of the Gaussian density profile. Spiral galaxies are not all the same and this parameter enables us to tailor the density distribution for every galaxy. It also gets us away from treating the galaxy as a simple point mass. As mentioned above this parameter only affects the shape of the curve in the inner region of the galaxy.
(c) The 1/e-width of the Gaussian for the energy scale variation; this is always much broader than that for the density.
(d) The height of the Gaussian for the energy scale variation profile.

Parameters (c) & (d) together affect the shape of the curve in the outer regions of the galaxy beyond around 10 kpc. The fitting procedure is usually carried out by eye.

1.12 Having four adjustable parameters, as mentioned in 1.11 above, may seem a lot and from that we might be expected to get a reasonable fit to any shape. However, the first two essentially define the density distribution and are fixed by the inner regions of the galaxy where Newtonian gravitation appears to work well. It is only the last two parameters, fitting the outer region of the galaxy, that tie down the energy scale variation. So in practice we only have two free parameters to fix the energy scale variation for each individual galaxy.

1.13 Our model is fairly well constrained and has a reasonably sound physical basis. It is two Gaussian distributions; one for the density and one for the energy scale variation. The same model is applied in the same way to the rotation curves of all spiral galaxies. So we have a standard model, which is applied in a standard way to all galaxies. There are no extra hidden parameters anywhere.

1.14 The parameters used to fit galaxy NGC 3198 are shown in Figure 18.4. The density distribution (brown curve) is chosen to be a Gaussian with a 1/e-width of 7.9 kpc. The energy scale variation (purple curve) is chosen to be a second Gaussian curve with a peak of 3.4 and a 1/e-width of 20 kpc. These parameters correspond to a dark matter interpretation for NGC 3198 of at least 80% dark matter and at most 20% normal baryonic matter. Our fit also gives an estimate of the mass of NGC 3198 of around 6×10^{11} solar masses.

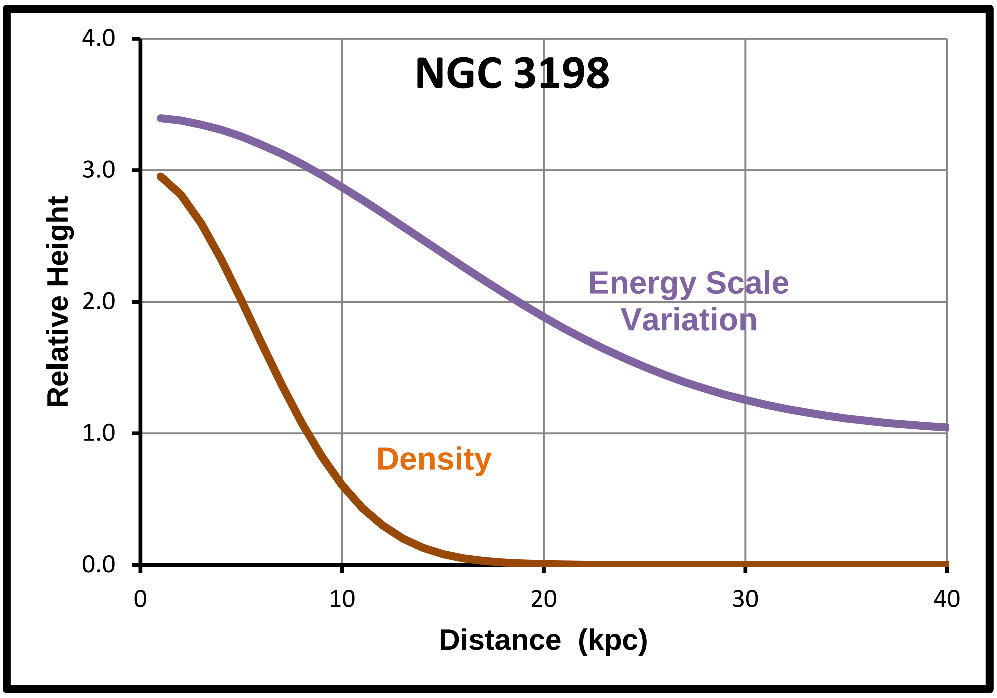

Figure 18.4. The profile of the Energy Scale Variation (purple curve) and the profile of the density distribution (brown curve) as used to calculate the red curve in Figure 18.5.

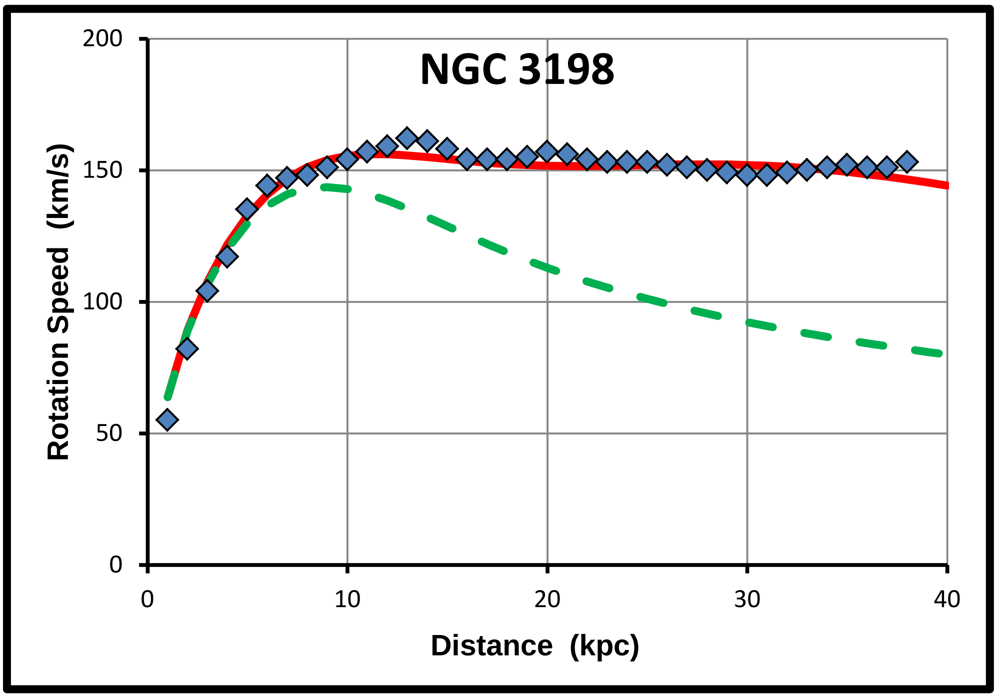

Figure 18.5. The observed rotation curve for galaxy NGC 3198. The blue diamonds are the observations; the green dashed curve is the expected curve for Newtonian gravity; the red curve is for an energy scale variation.

1.15 Figure 18.5 shows the the observations for NGC 3918 (the blue diamonds), the curve for Newtonian gravity (green dashed curve), and the rotation curve for our fit (solid red curve). The fit is, of course, not perfect. Nevertheless it is pretty remarkable considering the simple model and the observed lumpy structure of the galaxy.

1.16 Our model, with the identical fitting procedure and with the same four adjustable parameters, has been applied to a sample of 74 spiral galaxies. Good fits have been obtained in all cases.

1.17 Figures 18.6 & 18.7 show the rotation curves for a selection of 20 spiral galaxies out of the total of 74. The black diamonds are the observations; the green dashed line is the expected curve for Newtonian gravitation; the solid red line is the curve for an energy scale variation.

1.18 The fits are by no means perfect but they are pretty good considering the simple nature of the model coupled with the fact that spiral galaxies are not smooth disks. The fits tend to be worse in the inner regions where our simple model of a Gaussian density distribution is clearly not good enough. In principle we could probably obtain a more realistic density profile from observations of the brightness distribution across the disk of the galaxy. That could be plugged into the calculations to give a more realistic fit.

1.19 The rotation curves show a variety of shapes and very few can really be described as "flat". The deviations from the curves expected for normal Newtonian gravity only begin to show themselves beyond around 5 kpc. In most cases the galaxies in Figures 18.6 and 18.7 have been selected because their rotation curves go out to at least 20 kpc. The departure from Newtonian gravity is clearly apparent in all cases.

1.20 The topmost panels in Figure 18.6 show the rotation curves for our galaxy, the Milky Way, and our nearest neighbour, the Andromeda galaxy. We can see that the rotation speeds for Andromeda are higher than those for the Milky Way. This leads to the well-known conclusion that Andromeda is around twice as massive as our own galaxy.

1.21 In conclusion the rotation curves of spiral galaxies are well fitted by our conjecture that the energy scale can vary from location to location.

2 Summary

2.1 The simple model of a Gaussian density distribution and a Gaussian energy scale variation gives rise to rotation curves that are a good fit to the observed rotation curves of spiral galaxies.

2.2 The rotation curves show a range of shapes, a few of them can be loosely be described as "flat".

2.3 All the rotation curves return to the expected Newtonian fall off at large distances, albeit at a higher level.

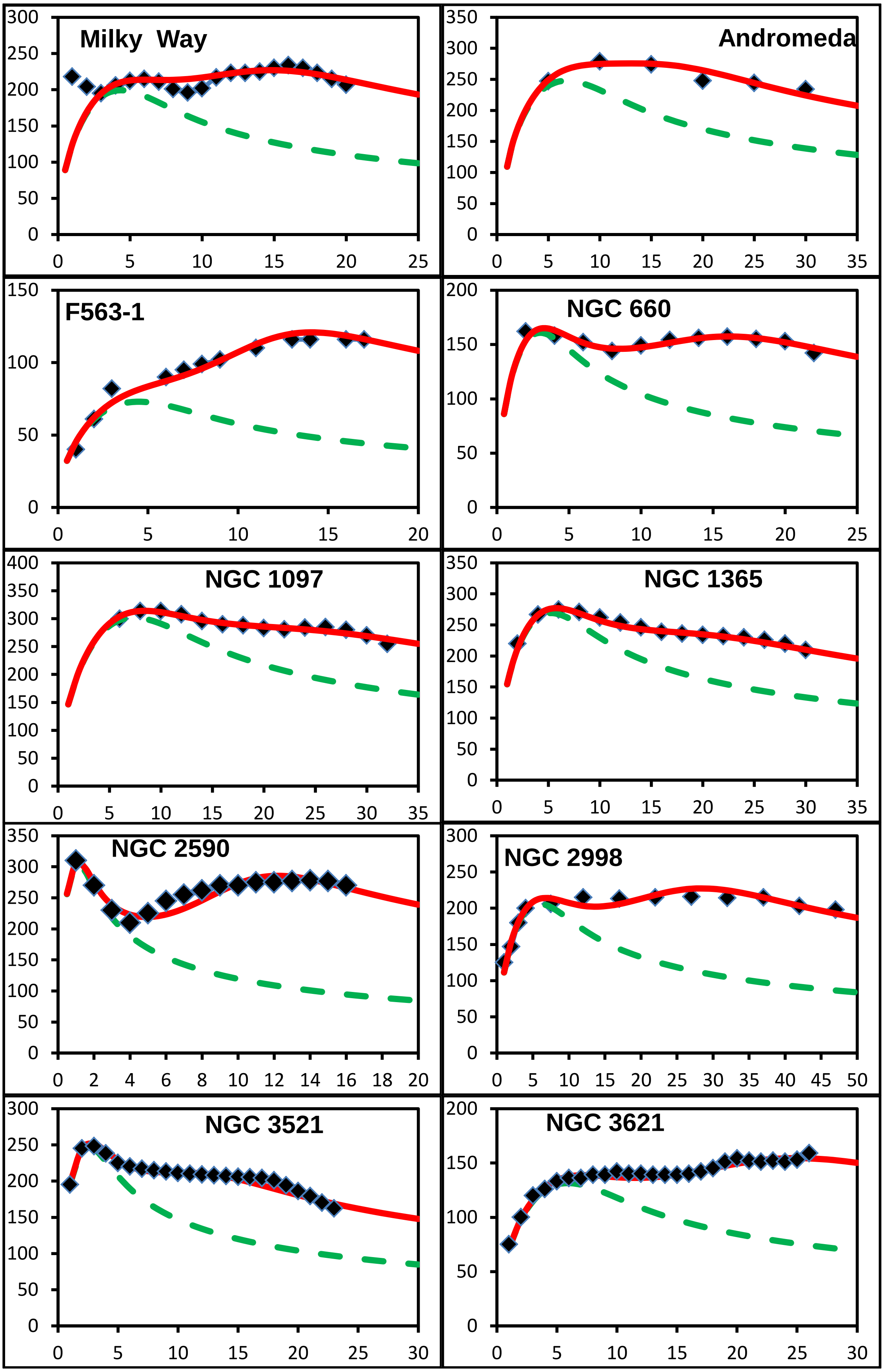

Figure 18.6. Rotation curves for a selection of spiral galaxies. Black diamonds are the observations; green dashed line is curve for Newtonian gravitation; Red line is fit for an energy scale variation. Horizontal axis is distance (kpc); vertical axis is speed (km/s)

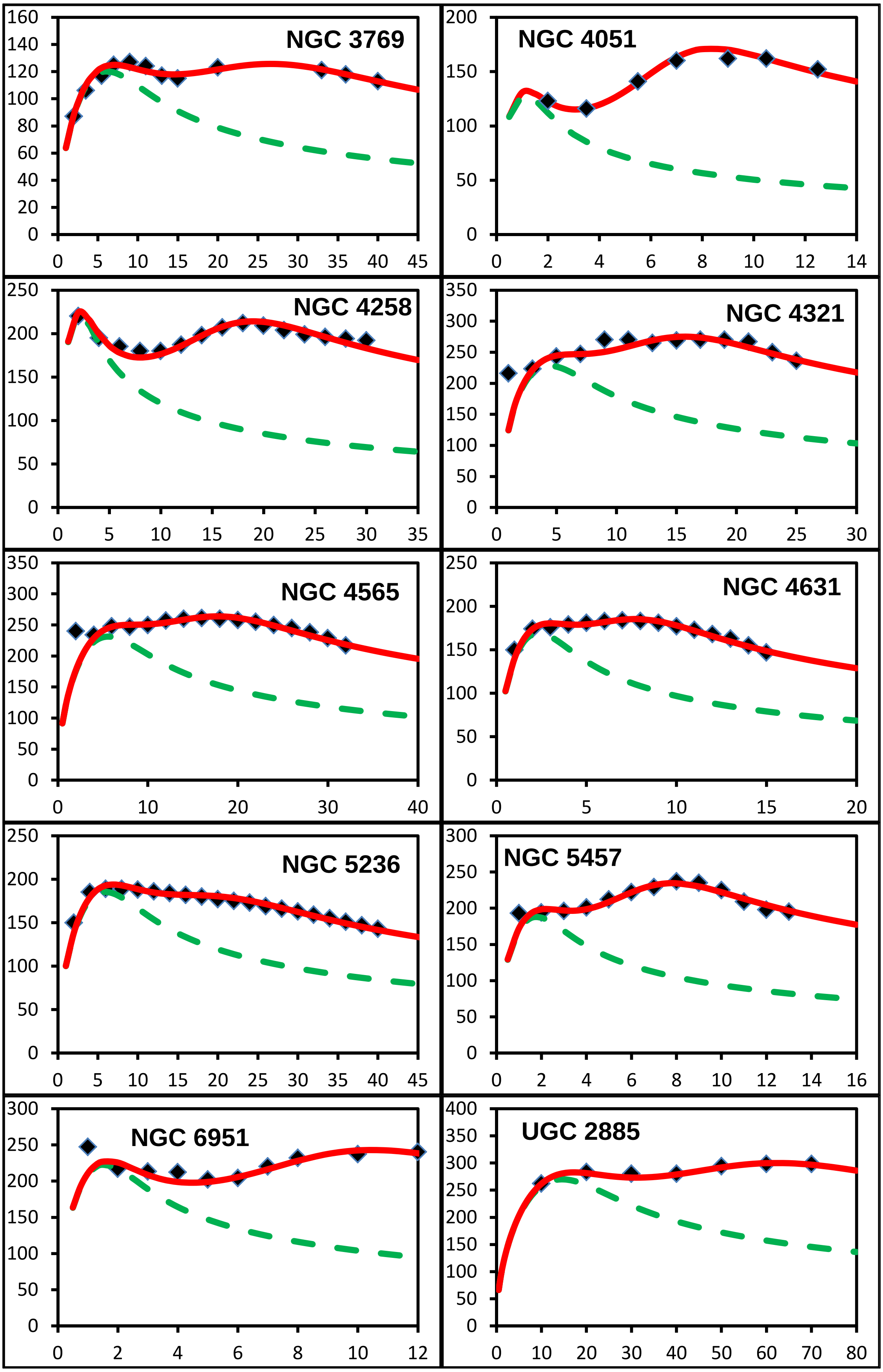

Figure 18.7. Rotation curves for a selection of spiral galaxies. Black diamonds are the observations; green dashed line is curve for Newtonian gravitation; Red line is fit for an energy scale variation. Horizontal axis is distance (kpc); vertical axis is speed (km/s).

19

Clusters of Galaxies

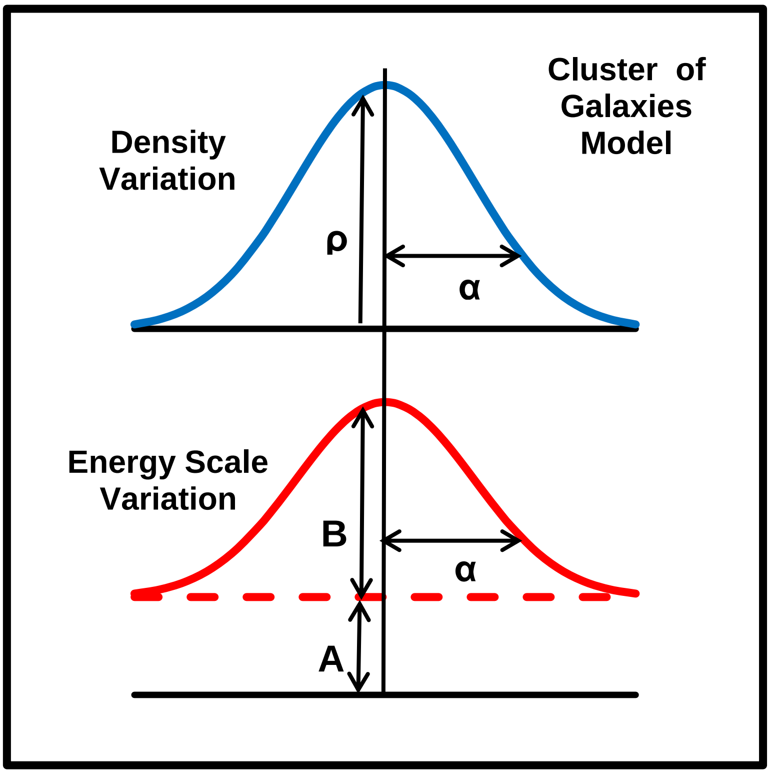

Figure 19.1. Model of a cluster of galaxies. The density distribution (blue curve) is a Gaussian. The energy scale variation (red curve) is another Gaussian with the same 1/e-width.

We revisit chapter "5: Clusters of Galaxies", and answer the question "how does our new idea dispense with the need for dark matter?"

6 The Energy Scale Variation Solution

1.1 Clusters of galaxies are sufficiently old to be relaxed systems and as such they should obey the virial theorem whereby the gravitational potential energy is twice the kinetic energy. Observations of clusters of galaxies show that the kinetic energy is in fact at least a factor of five too high for the potential energy. The galaxies should have sped away a long time ago and the clusters dispersed.

1.2 The dark matter solution is to place the cluster inside a vast halo of dark matter. The halo needs to be around five times the mass of the cluster to provide the required potential energy. Not only does the dark matter account for the high velocities of the galaxies but it also accounts for the X-ray emission from the gas and the gravitational lensing of more distant galaxies. Overall dark matter accounts well for the observations.

1.3 Our new solution is to embed the cluster of galaxies in an energy scale variation with roughly the same dimensions as the cluster. This is then sufficient to support the high velocities of galaxy members, the X-ray emitting gas, and the gravitational lensing.

1.4 Up to 90% of the mass of a galaxy cluster is in the gas; the galaxies themselves only account for around 10%. We can model the density distribution of the gas and galaxies by a Gaussian with a 1/e-width that matches the cluster. This is illustrated by the blue curve in the upper part of Figure 19.1. The density peaks at the cluster centre and falls off exponentially towards the edge.

1.5 We do not know the shape of the energy scale variation but it is reasonable to assume it is similar to the galaxy cluster itself. So we model the energy scale variation as another Gaussian with the same 1/e-width as the galaxy cluster. This is illustrated by the red curve in the lower part of Figure 19.1. Unlike the density distribution, which falls to zero at the cluster edge, the energy scale variation falls to a constant background value.

1.6 We can examine the velocities of the galaxies in our model in two different ways. Firstly, we can calculate the velocities the galaxies must have if they are in circular orbits around the cluster centre. The results of the calculations are shown in Figure 19.2. The green dashed curve is what is expected for Keplerian orbits; i.e. no energy scale variation, just Newtonian gravity. The red curves show the orbital speeds when we add in energy scale variations of various strengths. The number against each curve is the ratio of the height to the background level (B/A in Figure 19.1). It is clear from Figure 19.2 that the orbital speeds of the galaxies increase with the strength of the energy scale variation. So galaxies can have high speeds and still remain bound to the cluster. The orbits of the galaxies are not circular around the cluster centre; they are more randomised. Nevertheless Figure 19.2 demonstrates, in principle, how high speeds arise from energy scale variations.

1.7 Secondly, we can calculate the escape velocity; the velocity a galaxy must have to escape from the galaxy cluster. The results of these calculations are shown in Figure 19.3. It shows that a high velocity is needed to escape from the centre of the cluster, while a much lower speed is needed to escape from the edge. Again the green dashed curve is what is expected if there is no energy scale variation present; just Newtonian gravity. And, again, the red curves show the escape velocities for energy scale variations with different strengths, exactly the same as in Figure 19.2. It is clear that the escape velocities go up; galaxies must have much higher speeds if they are to leave the cluster.

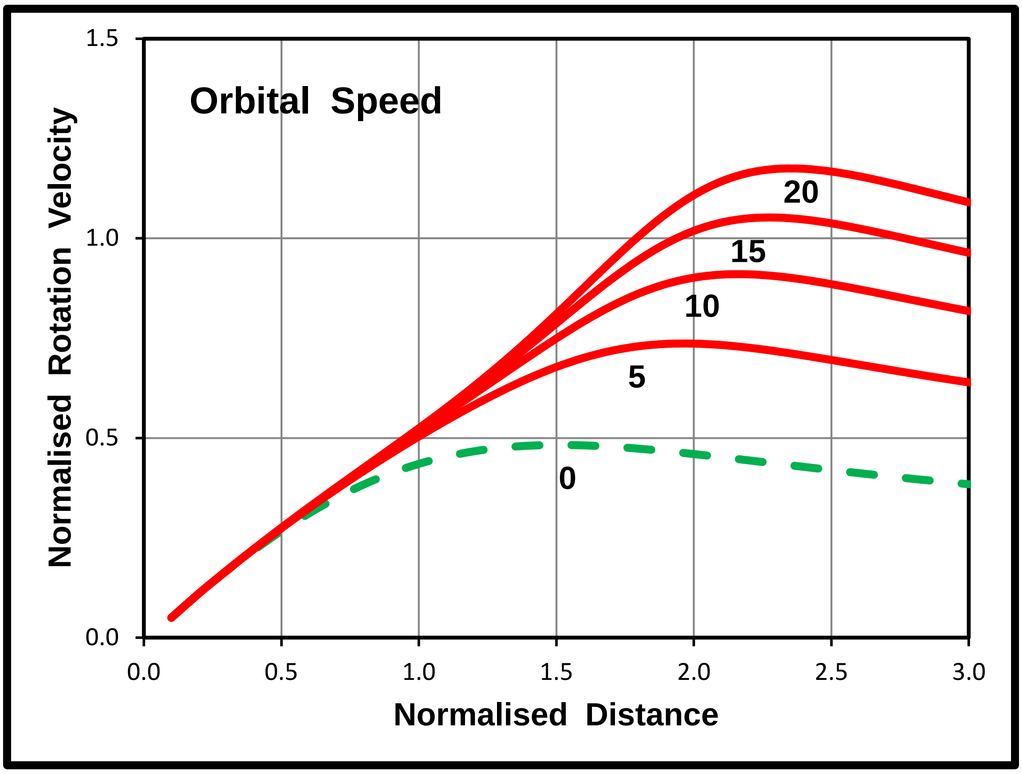

Figure 19.2. Calculated speeds for galaxies in circular orbits about cluster centre. Curves are for different strengths of the energy scale variation. The green curve represents Newtonian gravity, i.e. no energy scale variation.

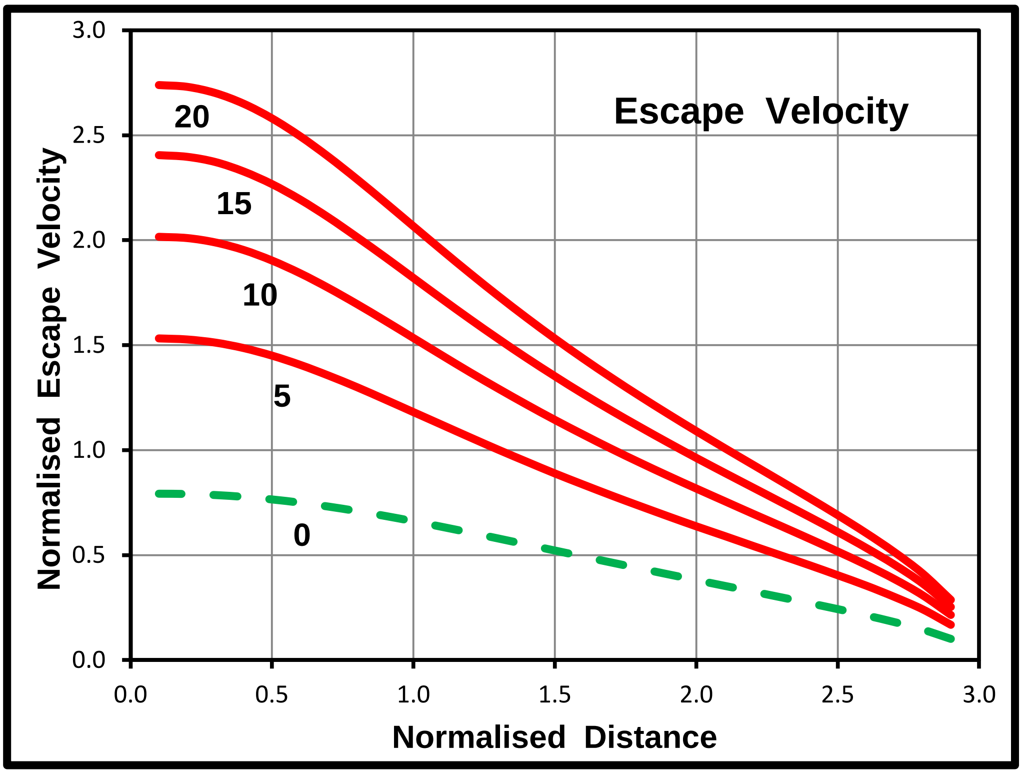

Figure 19.3. Calculated escape velocities for galaxies in a cluster of galaxies. Curves are for different strengths of the energy scale variation. The green curve represents Newtonian gravity, i.e. no energy scale variation.

1.8 Both calculations show how an energy scale variation solves the problem. Even though the galaxies are moving very fast they will not have sufficient speed to escape from the cluster. The galaxies are trapped within the cluster, which remains a stable and bound system. Overall the energy scale variation increases the gravitational potential energy such that the virial theorem is obeyed.

1.9 The energy scale variation also provides the gravitational force to hold the large amount of hot gas in hydrostatic equilibrium. It is sufficient to explain the X-ray emissions from the hot gas as observed in most clusters of galaxies.

1.10 The energy scale variation means the cluster behaves as it it has much more mass that is actually the case. This extra "effective" mass is sufficient to account for the observed gravitational lensing of more distant galaxies.

1.11 We do not have access to the data for actual clusters of galaxies. So we cannot make detailed calculations for any individual cluster. All we can say is that, in principle, our model calculations demonstrate that energy scale variations can explain everything that dark matter is invoked to explain.

2 Summary

2.1 Embedding a cluster of galaxies inside an energy scale variation of similar proportions solves the problem of the high velocities of individual galaxy members.

2.2 The energy scale variation increases the gravitational potential energy so that it is twice the kinetic energy and so that the virial theorem holds.

2.3 The additional gravitational potential provided by the energy scale variation also accounts for the gravitational lensing of remote galaxies and the X-ray emission from the hot gas.

20

Gravitational Lensing

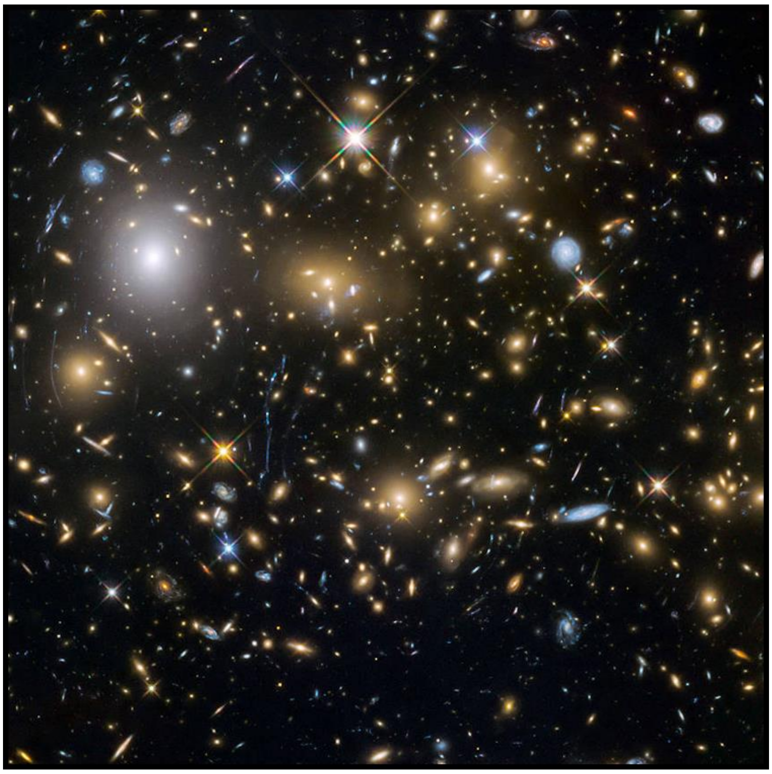

Figure 20.1. Hubble image of distant galaxies. The multiple small arcs of light are the gravitationally lensed images of more distant galaxies. (Credit: ESA/NASA)

We revisit chapter "6: Gravitational Lensing" and answer the question "how does our new idea dispense with the need for dark matter?"

1 The Energy Scale Variation Solution

1.1 The mass of clusters of galaxies as derived from the gravitational lensing of remote galaxies is between five and ten times larger than the observed mass of the galaxies and gas. The usual solution is to postulate the existence of between five and ten times the mass of the cluster in the form of dark matter.

1.2 Our new solution to this problem is to embed the cluster in an energy scale variation. This increases the effective mass of the cluster by a multiplicative factor, ξ, which then explains the gravitational lensing. If we choose this factor to be between five and ten then we end up with the same gravitational mass as for dark matter. So the gravitational bending of light is exactly the same as well.

1.3 This is illustrated in Figure 20.2. As before, the pink circle on the left represents the hot gas in the cluster and the blue ellipses are the galaxies. The shaded green circle in the middle represents the energy scale variation, which increases in strength towards the centre of the circle. The dark green circle on the right represents the cluster of galaxies embedded in the energy scale variation, which then acts as if its mass were increased by a factor, ξ.

1.4 Figure 20.3 illustrates how a light ray from a remote galaxy is bent by the cluster. The light ray can be thought of as approaching the cluster to within a distance, R, where it is bent through an angle, θ. Again the cluster of galaxies acts as a simple lens. In reality the bending does not happen at a single point; instead the light ray follows a curved path.

1.5 Not only does the energy scale variation increase the effective mass of the cluster for gravitational lensing, but the same increased mass provides the extra gravity for supporting the hot X-ray emitting gas.

1.6 An eye-ball comparison of Figures 6.2 & 6.3 (in chapter "6: Gravitational Lensing") with Figures 20.2 & 20.3 shows that the dark matter solution and the energy scale variation solution bend light rays in exactly the same way. However, the underlying physics is completely different.

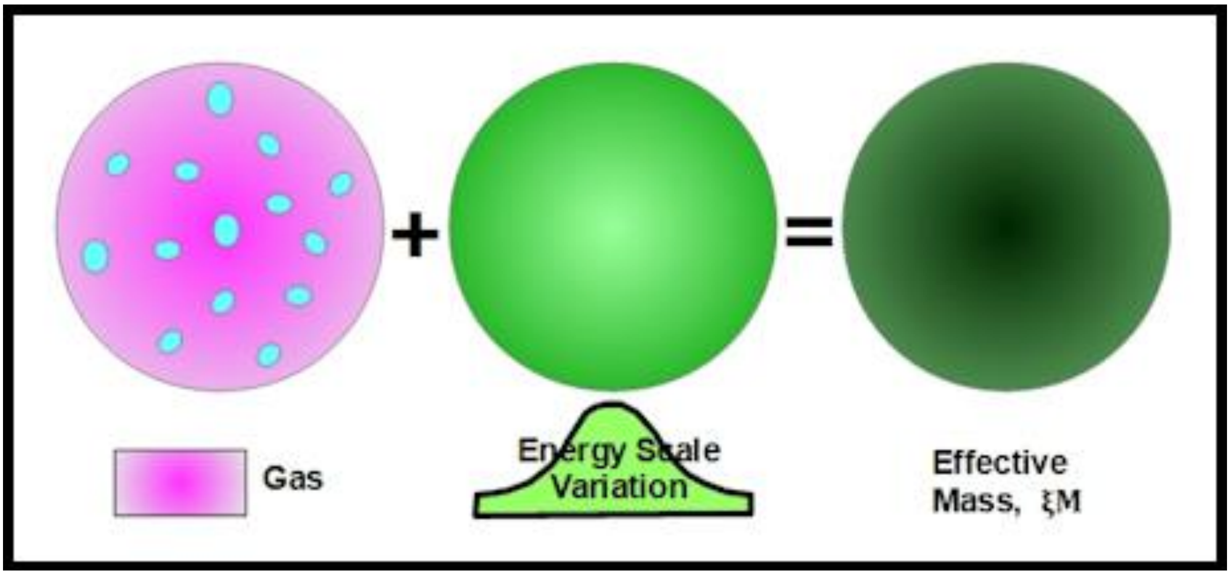

Figure 20.2. Schematic of how a cluster made of galaxies and gas, when embedded in an energy scale variation, gives rise to an object with a substantially larger mass.

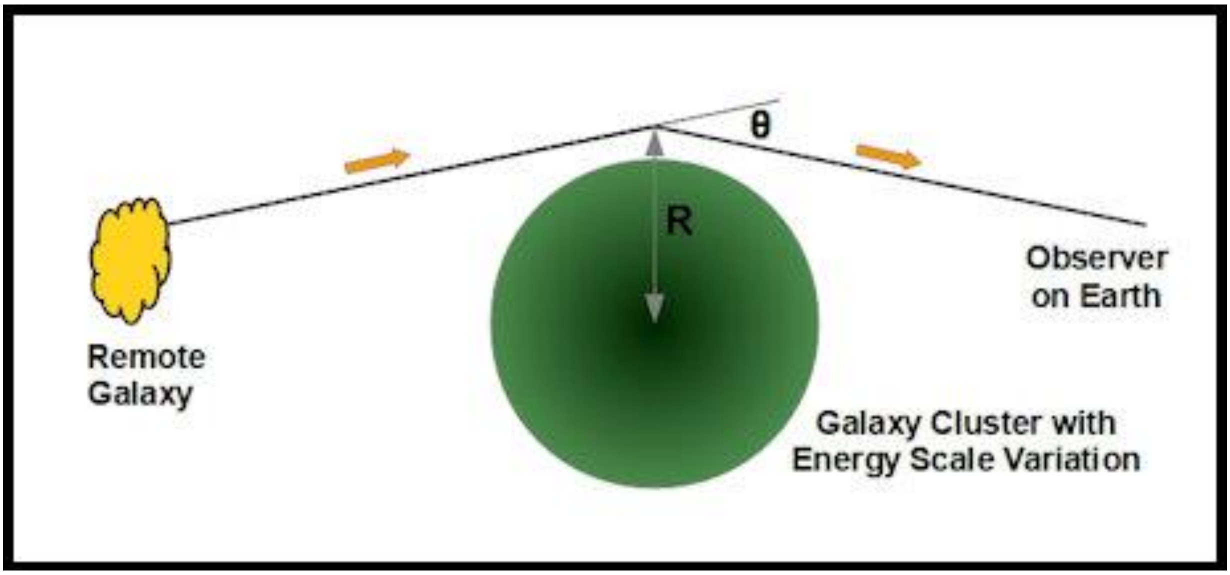

Figure 20.3. Schematic of the gravitational bending of light from a remote galaxy by a cluster of galaxies embedded in an energy scale variation.

2 Models

2.1 Gravitational lensing (both strong and weak) enables the distribution of the gravitating matter across the cluster to be determined.

2.2 Computer models have been built for the dark matter scenario. They work out the distribution that dark matter must follow to produce the observed gravitational lensing. The procedure is quite complex and often a grid of models has to be constructed, varying a number of parameters until a satisfactory fit is obtained.

2.3 Similar modelling techniques could be applied to our conjecture of energy scale variations. No such computer models exist at the moment, so this is very much an exercise for the future.

3 Summary

3.1 A cluster of galaxies embedded in a positive energy scale variation will behave gravitationally as if its mass were much greater. This can account for the gravitational lensing of remote galaxies by the cluster.

3.2 To date no detailed model calculations have been carried out to fit a variation of the energy scale to the observed gravitational lensing.

21

Collisions between Clusters of Galaxies

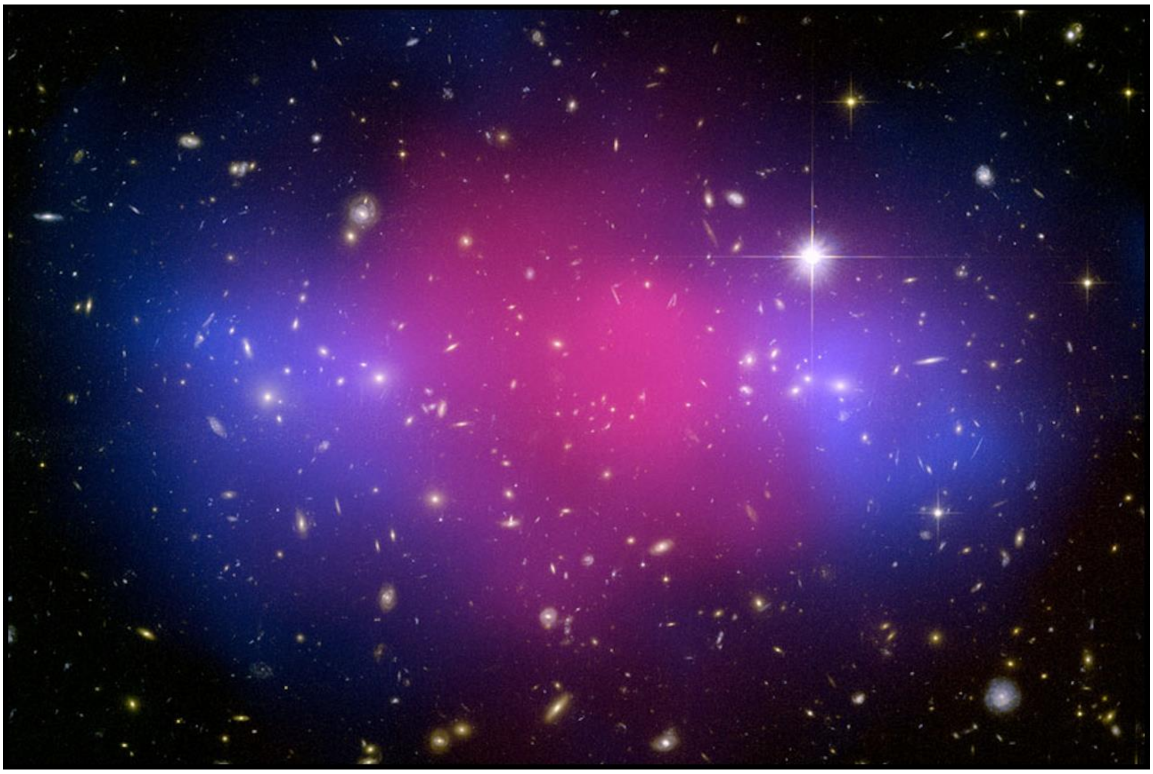

Figure 21.1. Hubble image of MACSJ0025, the collision of two clusters of galaxies. The pink area is the hot gas as revealed by the Chandra X-ray telescope. The blue areas are where the mass is located as revealed by weak gravitational lensing. (Credit: NASA, ESA, CXC, M.Bradac/UCSB, S.Allen/Stanford)

We revisit chapter "7: Collisions between Clusters of Galaxies", and answer the question "how does our new idea fit in with collisions between galaxy clusters?"

1 The Energy Scale Variation Solution

1.1 In clusters of galaxies the normal matter is divided between the galaxies and the gas that fills the entire cluster. As much as 90% of the mass is in the gas with as little as 10% in the galaxies. Following a collision between two clusters, the galaxies are observed to be unaffected and to pass straight through. The gas on the other hand collides and tends to get stripped out and left behind.

1.2 Clusters of galaxies are also thought to contain a huge amount of dark matter, somewhere between five and ten times the mass of the cluster. Weak gravitational lensing shows that in collisions the dark matter passes straight through and stays with the galaxies. This is odd for two reasons. Firstly, the dark matter in one cluster appears not to interact all all with the dark matter in the other cluster. And secondly we might have expected the dark matter to go with the gas as that's where the majority of the normal matter lies.

1.3 We now look at how our conjecture of energy scale variations explains collisions between clusters of galaxies. The position before a collision is illustrated in Figure 21.2. The galaxies are shown as light blue ellipses; the hot gas filling the cluster in pink; the energy scale variation is indicated by the green Gaussian profiles under each cluster.

1.4 As explained in chapter "7: Collisions between Clusters of Galaxies" the energy scale variations increase the effective mass of the clusters and provide the large gravitational wells needed to hold the gas in place and to stop the galaxies from escaping. The increase in the effective mass also accounts for the gravitational lensing.

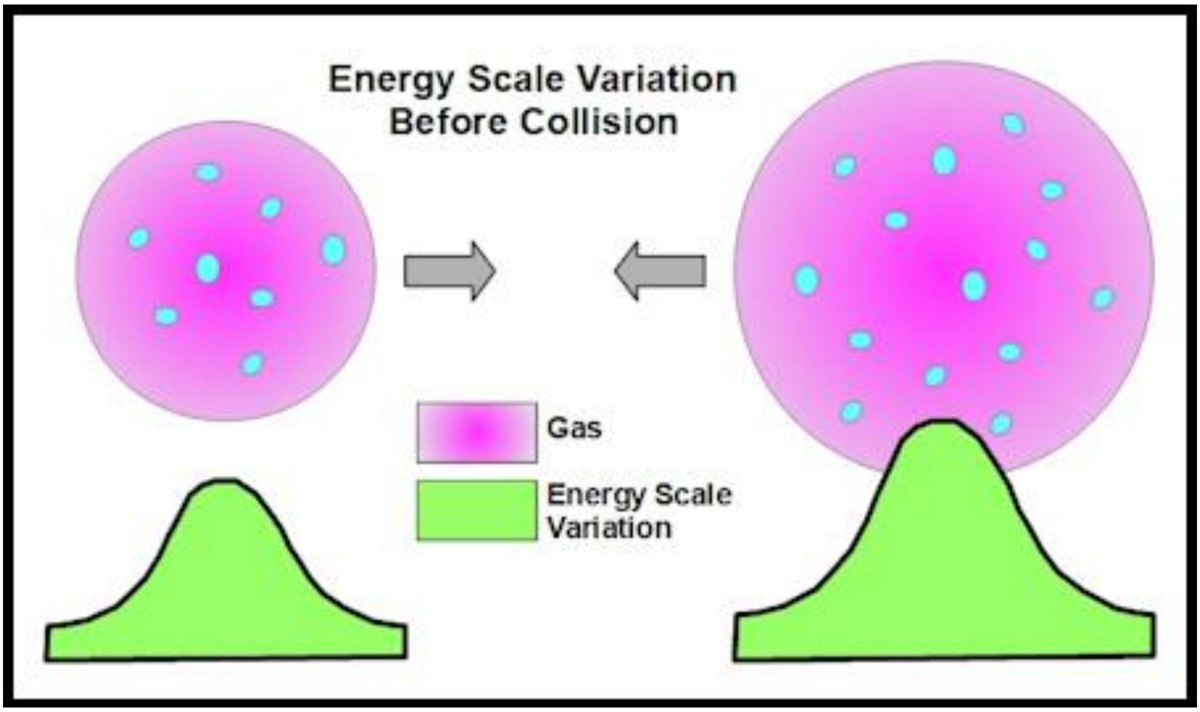

Figure 21.2. Two clusters of galaxies before collision. The galaxies (blue) are surrounded by hot gas (pink) and the whole embedded in energy scale variations (indicated by the green Gaussians).

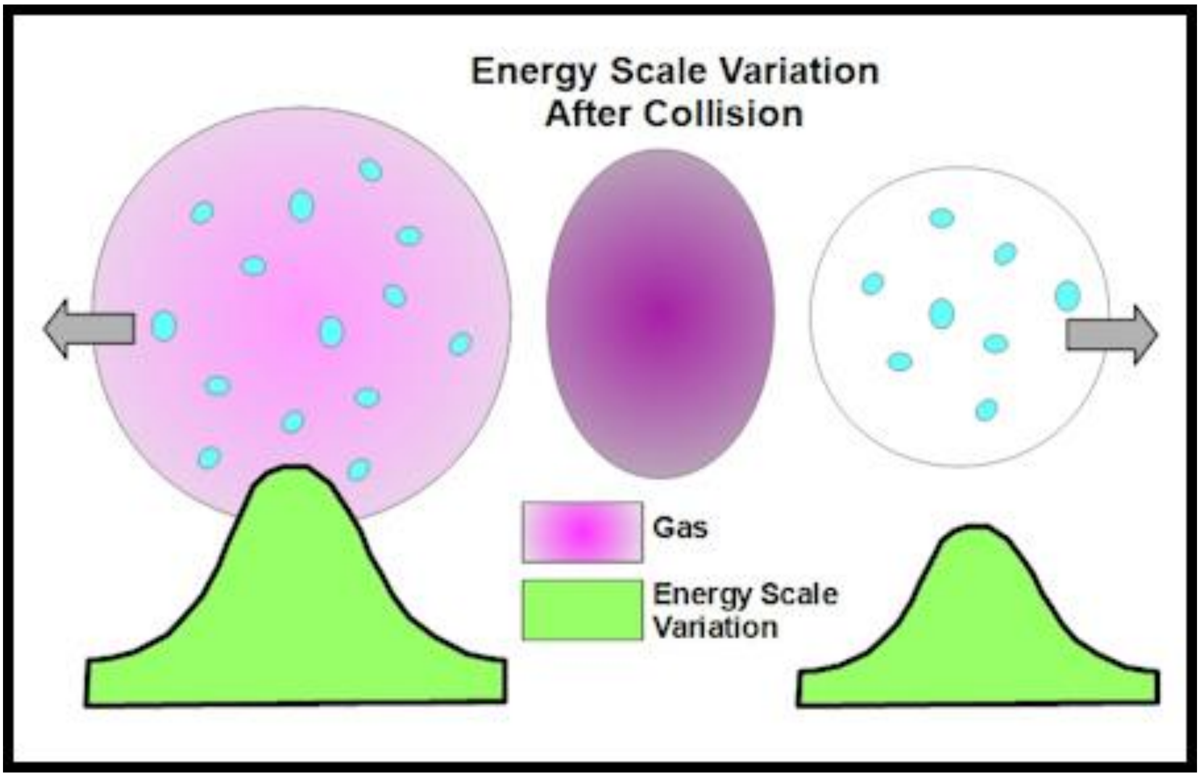

Figure 21.3. Two clusters of galaxies after collision. The galaxies (blue) remain embedded in the energy scale variations. The hot gas (pink) tends to get stripped out and left behind.

1.5 During the collision the galaxies pass straight through as before. The gas regions interact with one another during the collision and get left behind. The energy scale variations pass straight through much in the way one would expect two waves travelling along a vibrating string to behave.

1.6 The situation after a collision is illustrated in Figure 21.3. The energy scale variations pass straight through one another and continue on their way. The galaxies remain tied to the energy scale variations and continue to move apart as well. Most of the gas is stripped out and left behind.

1.7 If say 80% of the normal mass of each cluster was in the gas then, when the gas gets stripped out, each cluster loses around 80% of its mass. This reduces the depth of the gravitational potential well and the effective mass should now be insufficient to retain all the galaxies. The velocities of some of the galaxies should exceed the escape velocity and we would expect these galaxies to start start leaving the clusters.

1.8 Measurements of the clusters should show that the kinetic energy in the galaxies is too high to satisfy the virial theorem and that the clusters are beginning to disintegrate. This is a prediction of our conjecture and it can be tested right now, either using existing data or by obtaining fresh observations.

2 Summary

2.1 In collisions between galaxy clusters the energy scale variations pass straight through much in the way that two waves on a string pass through one another. The galaxies stay attached to the energy scale variations.

2.2 With much of the gas, which contains most of the mass, stripped out there may well be insufficient gravitating matter to hold the cluster together. The galaxies in the cluster are expected to disperse.

2.3 A prediction from energy scale variations is that galaxy clusters should show signs of break up after collisions. The matter remaining in the clusters should have insufficient gravitational potential to support the high velocity of individual galaxies.

22

Cosmic Microwave Background

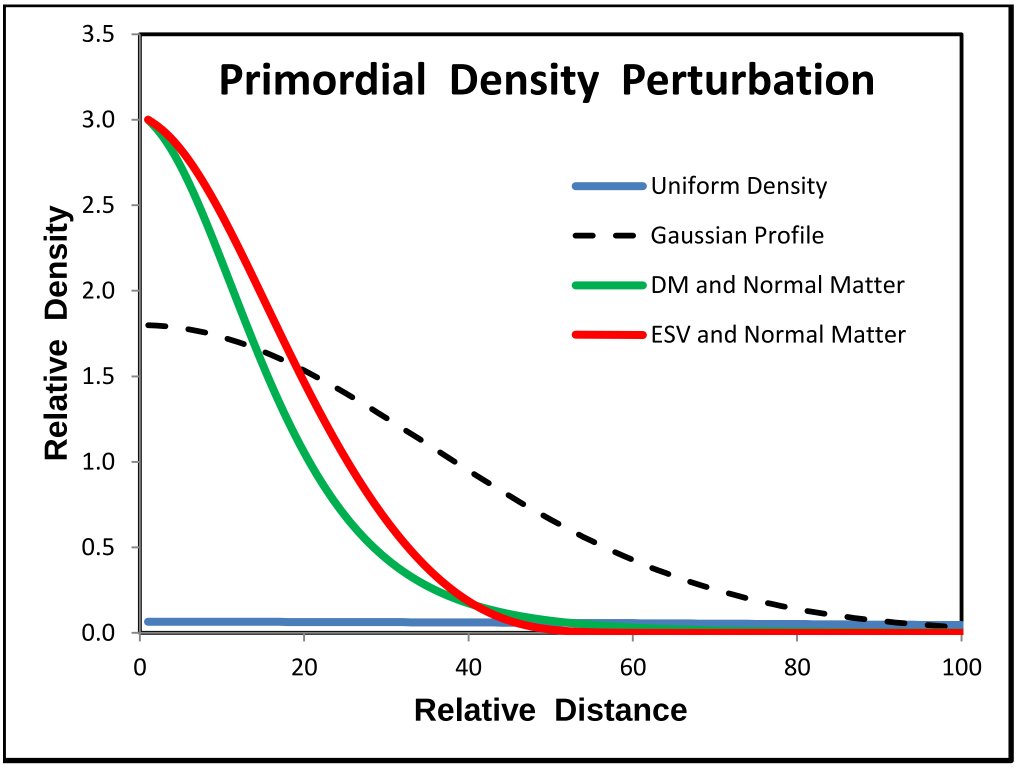

Figure 22.1. Density distributions of gravitational potential wells that cause the peaks seen in the power spectrum of the cosmic microwave background (CMB). The green curve is a density fluctuation caused by dark matter. The red curve is a density fluctuation caused by an energy scale variation.

We revisit chapter "8: Cosmic Microwave Background", and answer the question "how does our new idea solve the problems fixed by the addition of dark matter?"

1 The Energy Scale Variation Solution

1.1 The cosmic microwave background (CMB) shows fluctuations in temperature of around one part in one hundred thousand. These can be seen in Figure 8.1 of chapter "8: Cosmic Microwave Background". The power spectrum of the temperature fluctuations displays a number of peaks, shown in Figure 8.2.

1.2 The current interpretation of the peaks is based on the existence of dark matter, which does not interact with light or normal matter. Consequently well before the CMB gravity started attracting the dark matter into forming substantial gravitational wells. The normal matter underwent acoustic oscillations in these gravitational wells resulting in the observed peaks in the CMB power spectrum.

1.3 We can now look at how our conjecture of energy scale variations can give rise to the same result. We can do some simple computations for energy scale variations to see how good they are at pulling normal matter together and forming the required gravitational wells. These can then be compared to what dark matter can do.

1.4 Figure 22.1 shows the results of some simple calculations. The horizontal axis represents the distance from the centre of a spherical region of space. The blue line is the uniform density distribution for a sphere of normal baryonic matter. The dashed black line is a Gaussian density distribution for a concentration of dark matter, with 5 times the average density of normal matter. The green line is the density distribution for normal matter that has been pulled in by the dark matter. The red line is the density distribution for normal matter that has been pulled in by the energy scale variation.

1.5 All three lines (red, green, blue) are the density distributions for spheres with the same total mass. We can imagine the blue line is the starting density distribution, which is uniform across the sphere. The green curve is the result of the blue matter being pulled in by dark matter. The red curve is the result of the blue matter being pulled in by an energy scale distribution.

1.6 It is clear from Figure 22.1 that the green and red curves are very similar. Hence we can conclude that the density fluctuations produced by our energy scale variation are a close match to those produced by dark matter. If the density fluctuations are similar then the potential wells must be similar. Hence the acoustic waves that arise in the normal matter must be similar as must be the peaks observed in the CMB power spectrum.

1.7 There are no computer models (yet) for energy scale variations and no detailed computations have been carried out for the effects of their behaviour on normal matter around the time of the CMB. Nevertheless the simple work behind Figure 22.1 suggests that energy scale variations should do the job just as well as dark matter, and that acoustic variations should come about in much the same way.

2 Summary

2.1 The density fluctuations observed in the cosmic microwave background arise from normal matter that has fallen into gravitational wells .

2.2 Current theory uses dark matter as the source of the gravitational wells.

2.3 Energy scale variations act as gravitational wells and give rise to density fluctuations that are similar to those produced by dark matter.

23

Physical Cosmology

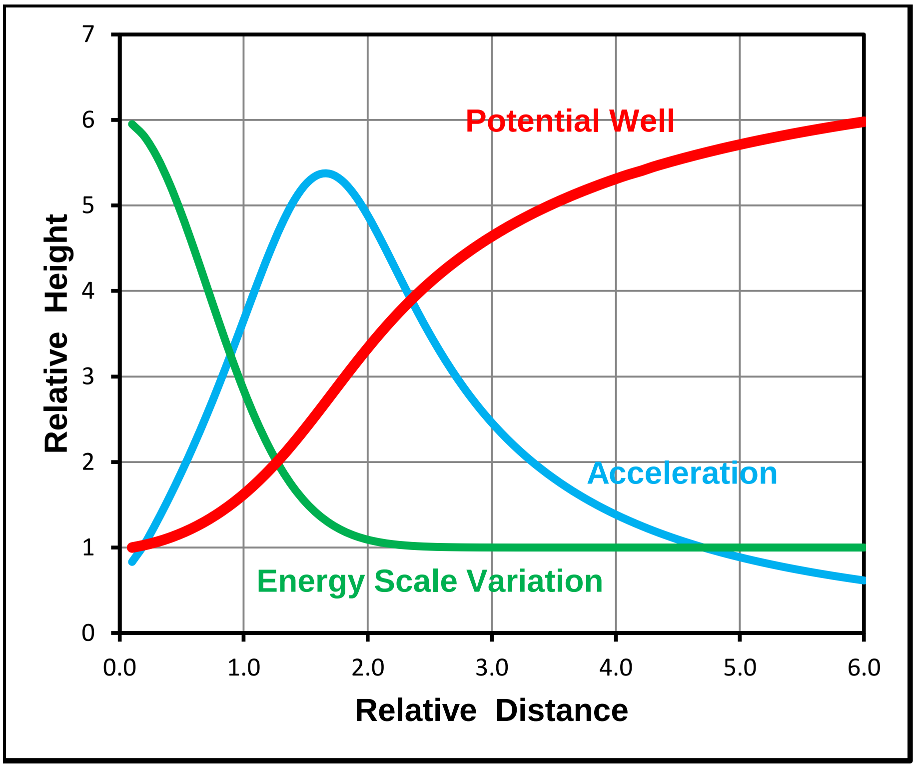

Figure 23.1. The gravitational potential well arising from a Gaussian energy scale variation in a homogeneous medium. The green curve shows the Gaussian profile of the energy scale variation. The blue curve is the strength of the gravitational acceleration. The red curve indicates the energy released when a particle falls into the gravitation well.

We revisit chapter "9: Physical Cosmology" and answer the question "how do energy scale variations solve the cosmological problems?"

1 The Energy Scale Variation Solution

1.1 We have seen that matter inside an energy scale variation has an enhanced gravitational effect on the matter outside. The stronger the energy scale variation the greater the effect. We can characterise this increase by a factor, γ, which can be much greater than 1.

1.2 In chapter "9: Physical Cosmology" we introduced the Friedmann equation which is one of the key equations that govern the way the Universe works. For our Universe containing only radiation and normal (i.e. no dark matter and no dark energy) we can write the Friedmann equation (9.1) as

$$\left(\frac{\dot{a}}{a}\right)^2 = H^2 = \frac{8\,\pi\,G}{3\,c^2}\{\varepsilon_R + \varepsilon_B\}\,\gamma \tag{23.1}$$

where a is the length scale factor; $\dot{a}$ the rate of change of the scale factor; H the Hubble parameter; ε_R the energy density for radiation; ε_B the energy density for normal baryonic matter; γ the strength of the energy scale variation.

1.3 This is different from the Friedmann equation we saw in chapter 9 in that the energy density contains no terms for dark matter or dark energy. Instead we have a multiplicative factor γ.

1.4 If we set $\gamma = 6 = 1 + 5$ then this compensates for dark matter, which is generally thought to have around 5 times the mass of normal matter. This is applying our maxim "multiply; don't add" from chapter "17: How It Works ". With our γ factor in place the Friedmann equation can explain the behaviour of the Universe from just after the Big Bang up to an age of at least 8 billion years. During this period the energy density of dark energy is too small to have any effect. From 8 billion years to the present time the Universe appears to be accelerating and a term for dark energy then becomes important.

1.5 Figure 23.1 illustrates the way that an energy scale variation creates a gravitational well in a homogeneous distribution of normal matter. We start with a density distribution that is the same across the region. Without an energy scale variation there would be not nett acceleration. But with the addition of an energy scale variation (green curve) a gravitational acceleration towards the centre is introduced. The red curve shows the amount of energy released when matter is attracted towards the energy scale variation. This illustrates how an energy scale variation can mimic the role traditionally assigned to dark matter.

1.6 In chapter "9: Physical Cosmology" we saw there are 4 problems relating to there not being enough matter in the Universe. We can now see how our idea of energy scale variations deals with these.

1.7 Problem 1: nucleosynthesis. We saw that arguments from nucleosynthesis and the CMB demonstrate that the amount of normal matter in the Universe at the time of the CMB can be only around 10% of that required for a flat Universe. This density is too small for the Universe to be flat and to have the critical density. However, our γ factor enables us to increase the effective density. If we choose a value of around 10 then this means the effective energy density is critical and the Universe is flat. At the same time we have not changed to amount of normal matter in the Universe so the creation of the elements at the time of nucleosynthesis is unchanged and proceeds exactly as before. So choosing a value of around 10 for our energy scale variation factor has exactly the same effect as adding in large amounts of dark matter. The correct proportions of the elements get created during nucleosynthesis. Problem 1 is solved.

1.8 Problem 2: the age of the Universe. With no dark matter the age of the Universe as computed using models such as the ΛCMD model turns out to be only around 5 billion years. This is clearly impossible as we know of starts that are at least 12 billion years old. However, we know that our γ factor in the Friedmann equation compensates for the dark matter. So a value of around 10 means that the evolutionary models of the Universe containing only normal matter should mimic those with dark matter and lead to today's Universe with an age of 13.8 billion years and with the oldest stars having ages of around 13 billion years. Computer models based on energy scale variations do not exist so we must wait for detailed calculations to be carried out. Nevertheless models based on the Friedmann equation should give the required result. Hence we strongly believe that Problem 2 is solved.

1.9 Problem 3: baryonic acoustic oscillations. The peaks observed in the power spectrum of the cosmic microwave background are believed to come from the oscillations of normal matter in the gravitational wells formed from dark matter. We saw how energy scale variations solve this in chapter "22: Cosmic Microwave Background". If our energy scale variation factor has a value of around 10 then it can give rise to gravitational wells that result in the required acoustic waves in the normal matter. Instead of dark matter forming the gravitation wells our energy scale variations do exactly the same job. No detailed computations have been carried out on this but we strongly believe these should be successful and that Problem 3 is solved.

1.10 Problem 4: flat Universe. We know that the energy density from normal matter and radiation is way below the critical energy density that is required for the Universe to be flat. However, by choosing our energy scale factor, γ, to have a value around ten we can reach the critical value required by the Friedmann equation. A modest value for our factor means radiation and normal matter act as if they had the critical energy density. We have a flat Universe once more and Problem 4 is solved.

1.11 In principle, all four problems can be solved by our multiplicative γ factor, we do not need to add in any non-baryonic dark matter. Detailed calculations have not been carried out as these require substantial modification of the code for existing computer models. Hopefully such calculations will be carried out in the near future.

2 Summary

2.1 Arguments are presented as to how variations in the energy scale can explain the four areas of physical cosmology where dark matter is currently used, namely:

(1) nucleosynthesis
(2) age of Universe
(3) baryon acoustic oscillations
(4) flat Universe.

2.2 The arguments are qualitative in nature. We really want to do the hard quantitative work and show that energy scale variations can do the job, but the theoretical models are not available yet nor are the relevant computer models.

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The Growth of Structure

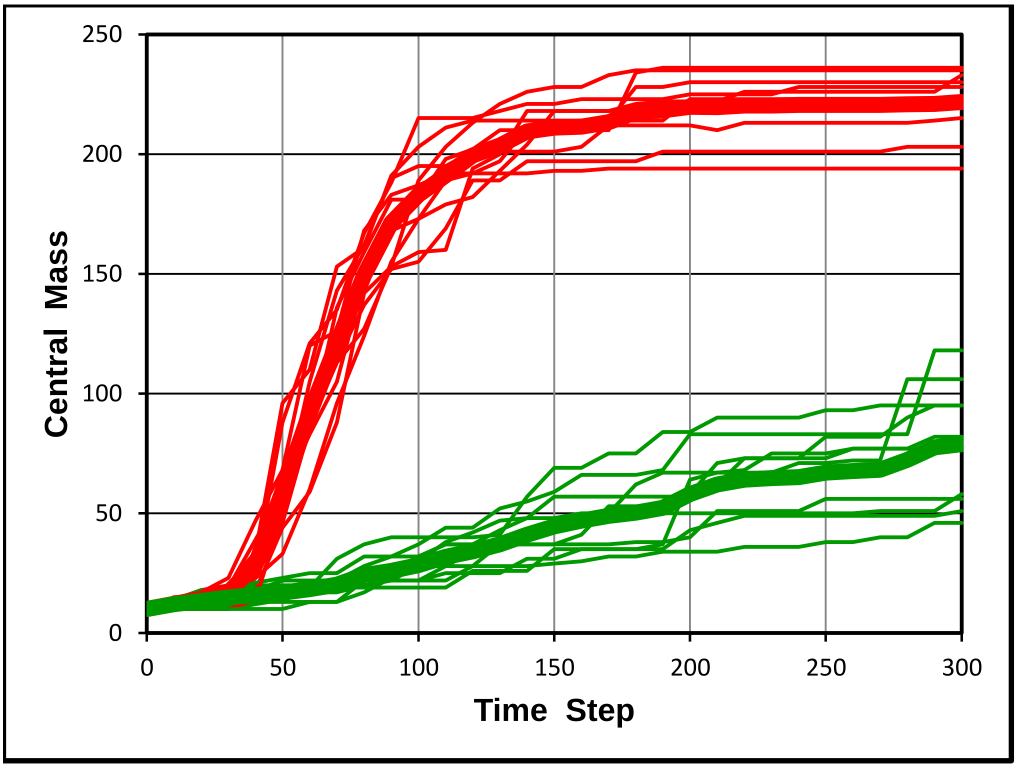

Figure 24.1. Simulations of the growth of structure. The green lines are for models with matter only. The red lines are for models with matter and an energy scale variation. The thick lines are the average of the runs.

We revisit chapter "J: Growth of Structure", and answer the question "how does our new idea dispense with the need for dark matter and still enable structures to grow?"

1 The Energy Scale Variation Solution

1.1 At the time of the cosmic microwave background (CMB), some 380,000 years after the Big Bang, the fluctuations in the density distribution were very small, around one part in 100,000. Gravity acting on this normal matter alone would not have had sufficient time to form the galaxies and other structures that are known to have been in place by one billion years; galaxies could only have formed much later on. If dark matter is added at a level of between five and ten times that of normal matter then the extra gravity would explain the time line of structure formation.

1.2 It is generally accepted that structures in the Universe grow in a bottom up manner: small objects are built first, larger objects are built later on. It is also generally accepted that normal matter on its own cannot form structures fast enough to match the observed time scales. The current way of solving this problem comes from the dark matter hypothesis whereby the existence of large amounts of dark matter provides the needed gravitational attraction.

1.3 We can now see how our alternative idea of energy scale variations solves the problem by providing the additional gravitational force that shortens the time required to build the observed cosmic structures.

1.4 If energy scale variations existed then they would have acted as gravitational potential wells and assisted the formation of structures, in the same way as dark matter. This was explained in chapter "P2: How It Works". If we have a homogeneous Universe, where the density is the same everywhere, then there are no density fluctuations and so nothing for gravity to work on. However, if we also have energy scale variations then matter away from them feels a strong gravitational attraction towards them and so they start growing.

1.5 As with the dark matter solution structure grow in a bottom up manner. Small objects are created very early on, such as the first stars. Larger objects form much later, such as the first galaxies.

2 Model Computations

2.1 We can investigate the way that energy scale variations speed up the process of structure formation using a simple model. We take a collection of 250 particles arranged randomly in a flat disk, given them small random motions, and follow their evolution. We do this for our two scenarios. Firstly, we work with just Newtonian gravitation and watch how this slowly brings the particles together. Secondly, we add in an energy scale variation and observe how this dramatically speeds up the rate at which the particles come together.

2.2 An example of one random simulation is shown in Figure 24.2.
The right panels show the evolution of the 250 particles with just Newtonian gravitation. The central mass starts with a value of 10; after 100 time steps this has grown to around 30; after 300 time steps it has reached 75; growth is slow and roughly linear.

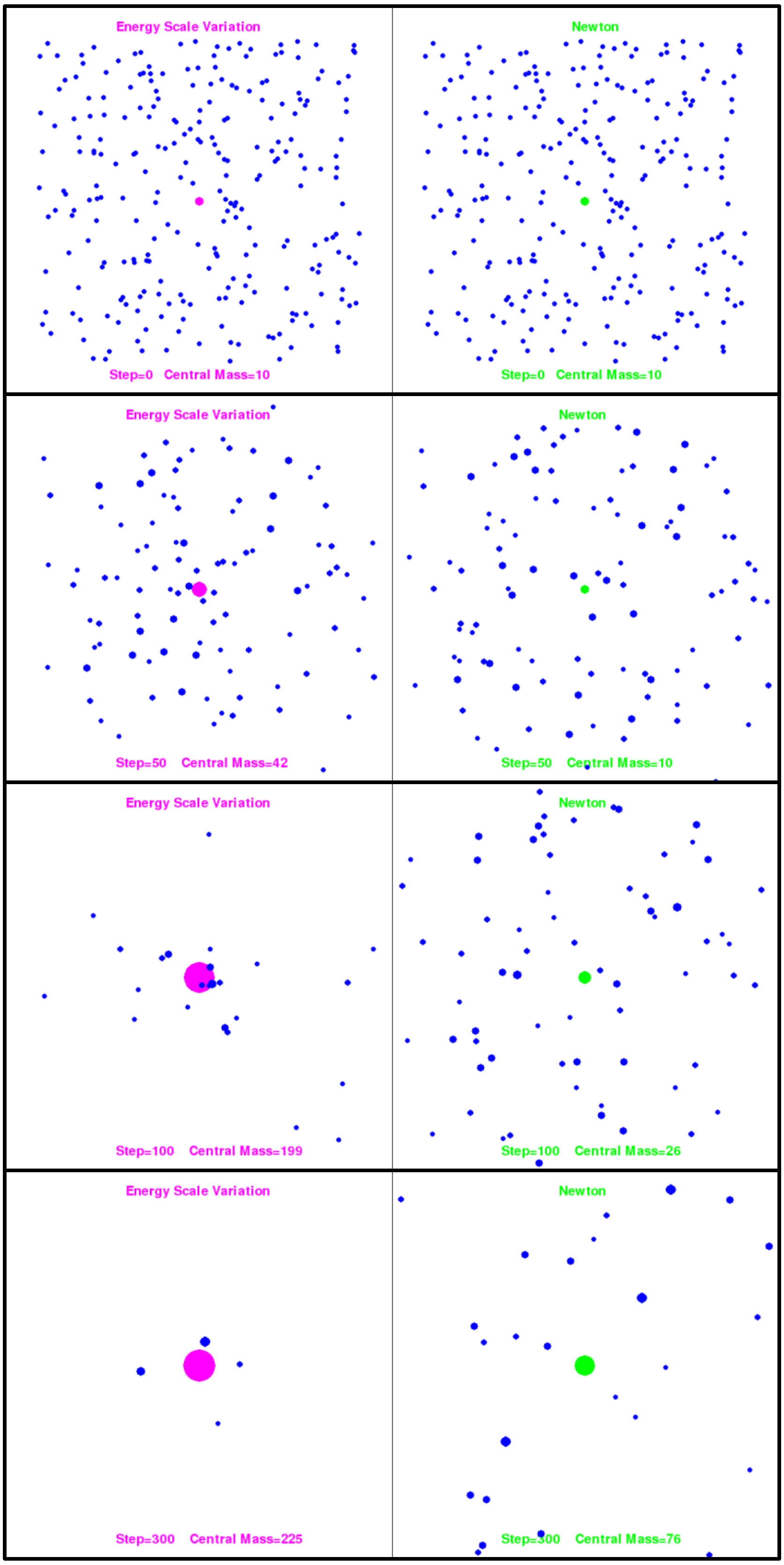

Figure 24.2. Simulation of structure formation using 250 particles with the same mass but random positions and motions. The right panels show the evolution for just Newtonian gravitation. The left panels show the evolution for Newtonian gravitation plus an energy scale variation. The different panels show the position at times: 0; 50; 100; 300.

2.3 The left panels show the same 250 particles but with the addition of an energy scale variation. Now after 100 time steps the central mass has grown to around 200 or 80% of the available mass; after 300 time steps it has grown slightly more to 225, or 90%. Growth is significantly more rapid that for just Newtonian gravity.

2.4 Figure 24.1 shows the growth for several different runs of the simulation. It is clear that the additional of an energy scale variation makes a large difference (about a factor of 10) to the rate at which the central mass can grow.

2.5 There are no computer codes in existence that model the evolution of the Universe with energy scale variations. However, it is to be expected that such models would follow the simple two-dimensional simulation presented here, which show that energy scale variations can result in a Universe that matches modern day observations.

2.6 We expect there to be energy scale variations where the energy scale is below than background average. The gravitational attraction in these regions is below the average which results in material being sucked out of them. Over the lifetime of the Universe these locations become voids or regions where there is very little matter and only a small number of galaxies.

3 Summary

3.1 Energy scale variations in the early Universe act as gravitational wells and provide locations where the gravitational attraction is enhanced.

3.2 Simple computations demonstrate that energy scale variations speed up the formation of structure compared to plain Newtonian gravity.

3.3 Energy scale variations can do the job currently attributed to dark matter and enable the Universe for form structures within the observed time frame.

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Summary

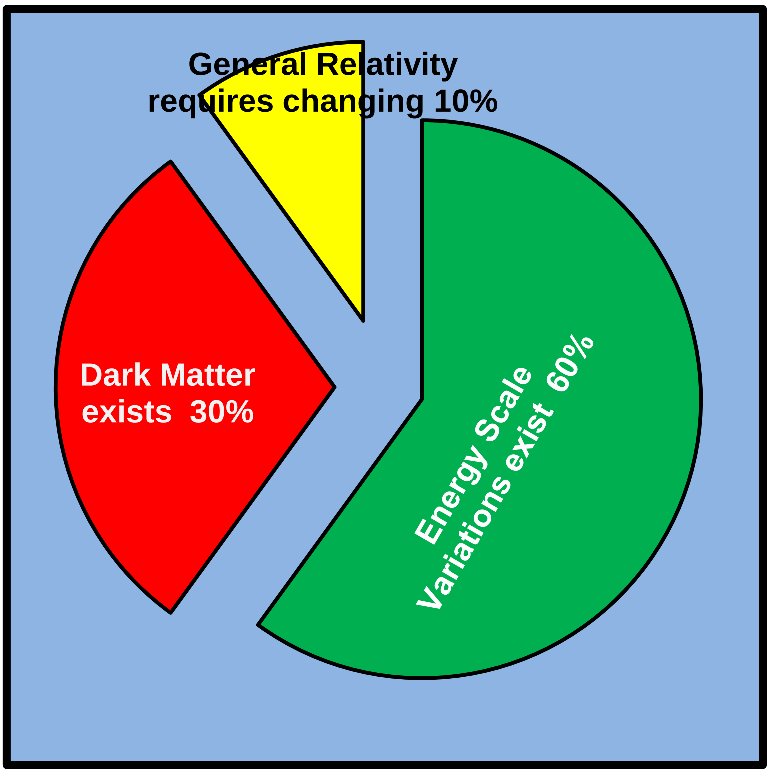


Figure 25.1. A somewhat biased view of the probability of the different options for explaining the astronomical observations with missing matter problems.

We summarise where we have got to with dark matter and energy scale variations.

1 Where we've got to

1.1 We have seen that the measurement of any physical quantity is made up of two parts: (a) a number, and (b) the units that relate to the quantity. The units can be expressed in terms of just seven scales that make up the International Systems of Units (SI units); these scales include length, time, and mass.

1.2 We are interested in energy rather than mass and we find it natural to switch to working with the energy scale rather than the mass scale. In terms of the length, time, and mass scales, the units of energy involve all three ($M\ L^2\ T^{-2}$). But when we switch to working with the energy scale, energy is just energy (E).

1.3 Physics involves a large number of constants and in this book we take it as read that all of these constants are fixed; none of them vary anywhere or at any time. So both the speed of light and the gravitational constant are absolute constants.

1.4 When we look at the scales there is no generally accepted evidence that either the length scale or the time scale vary. The question of whether the energy scale varies is open and the possibility of variations in the energy scale is where we step in to explain the dark matter scenarios of astronomy.

1.5 We have seen how the assumptions of a simple Gaussian shape for an energy scale variation coupled with a simple Gaussian density distribution are all that is needed to explain the observed rotation curves of spiral galaxies. These assumptions can be extended to explain the high velocities of galaxies in clusters.

1.6 We have also seen how variations in the energy scale can, in principle, explain the other scenarios of: gravitational lensing; cluster collisions; cosmic microwave background; physical cosmology; growth of structure.

1.7 Overall we should be happy that our conjecture of variations of the energy scale provides a consistent and coherent explanation to the astronomical observations where dark matter is invoked. Our conjecture deserves to be taken seriously, and it deserves to be investigated further.

2 Key Points

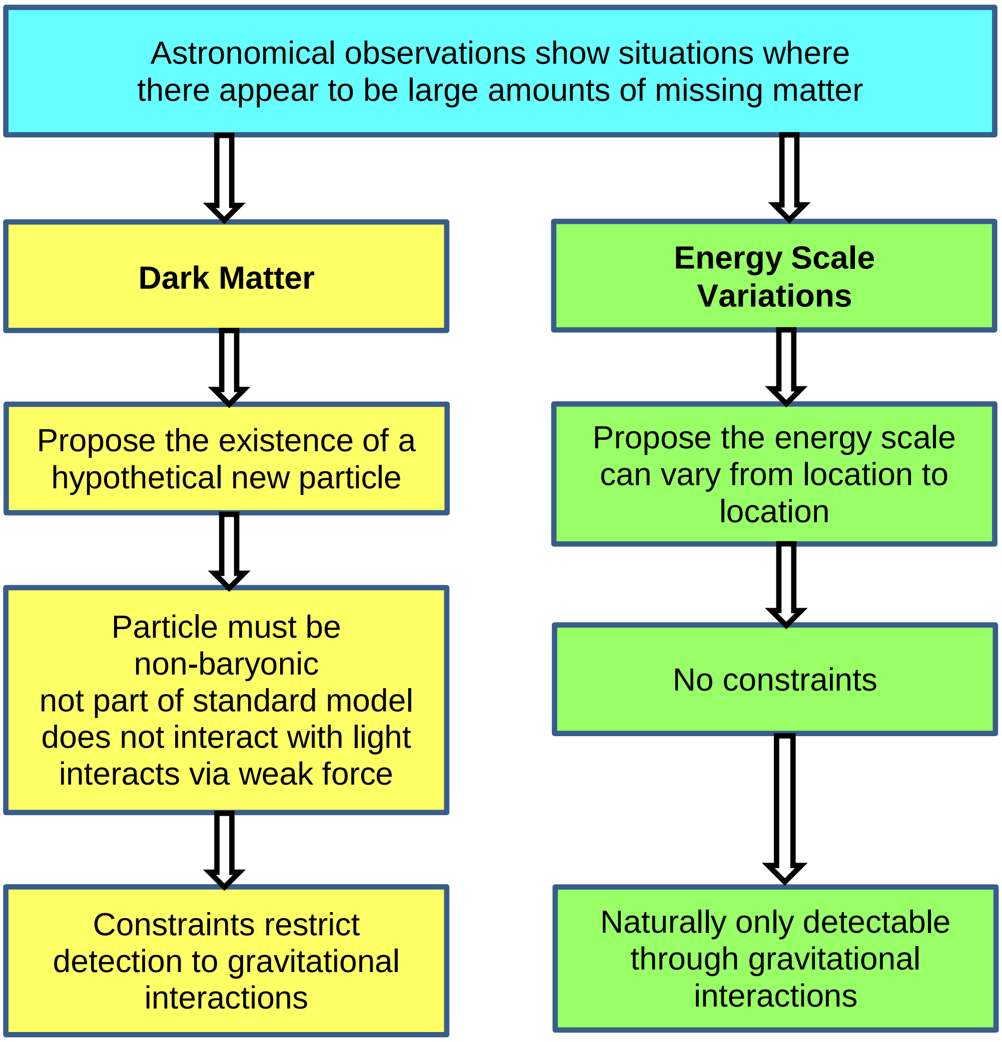
2.1 The following table lists the key points for our conjecture.

No	Point
1	The energy scale can vary from location to location
1a	a) The length scale does not vary
2b	b) The time scale does not vary
2	The constants of physics do not vary
2a	a) The speed of light does not vary
2b	b) The constant of gravitation does not vary
3	The laws of physics do not vary
3a	a) No change to Newton's law of gravity
3b	b) No change to Einstein's general relativity

2.2 We assume that only the energy scale varies from location to location. The remaining scales of physics remain fixed, in particular the length scale and the time scale.
We assume that all the constants of physics are constant and that none of them varies in any way. In particular both the speed of light and the gravitational constant are constant.
We assume that all the laws of physics are unchanged. In particular we are changing neither of Newton's law of gravity nor Einstein's general theory of relativity.

3 Hypotheses

3.1 The following illustration summarises how the hypotheses for dark matter and energy scale variations came about.



3.2 Dark Matter. The existence of dark matter was postulated to explain the missing mass in spiral galaxies and clusters of galaxies. More and more constraints were added as more and more observations came in. Theses constraints now include: it does not interact with light; it is non-baryonic; it only interacts with normal matter through gravity or possibly the weak nuclear force; it accounts for between 5 and 10 times more matter/energy than normal matter; it can clump together to form haloes, but not complex structures; it only interacts with itself weakly.

3.3 Energy Scale Variations. The existence of variations in the energy scale was postulated to explain the rotation curves of spiral galaxies. If the energy scale can vary then such variations can only be detected through gravity; this is a natural consequence and not an imposed constraint. Other scenarios were looked at to see if energy scale variations could provide explanations there as well. No constraints have been added.

4 Explain the Observations

4.1 Both the hypothesis of dark matter and our conjecture of energy scale variations can explain all the observational scenarios where dark matter is currently invoked. This is shown in the following table.

Observation	Dark Matter	Energy Scale Variations
Galaxy Rotation Curves	Yes	Yes
Galaxy Clusters	Yes	Yes
Gravitational Lensing	Yes	Yes
Cluster Collisions	Yes	Yes
Cosmic microwave background	Yes	Yes
Physical Cosmology	Yes	Yes
Growth of Structure	Yes	Yes

5 Forces and Interactions

5.1 The following table summarises the forces of physics and whether interactions occur.

Force	Dark Matter	Energy Scale Variations
Strong Nuclear	No	Yes
Weak Nuclear	Perhaps	Yes
Electromagnetic	No	Yes
Gravity	Yes	Yes

5.2 Dark matter interacts mainly through gravity. The most popular form for dark matter is the WIMP (weakly interacting massive particle), a particle that also interacts through the weak force. The experiments currently searching for dark matter particles are usually based on the predicted outcomes for weak nuclear interactions between normal matter and dark matter.

5.3 A variation in the energy scale doesn't affect particles or the forces of nature, so all types of interaction carry on as normal.

6 Observational Scenarios

6.1 The following table summarises how dark matter and energy scale variations explain the missing matter problems thrown up by observations.

Observation	Dark Matter	Energy Scale Variations
Spiral Galaxies Rotation curves do not follow law of gravity	postulate a massive halo of dark matter surrounds every galaxy	postulate galaxy is embedded in an energy scale variation
Galaxy Clusters High velocities of galaxies do not follow the virial theorem.	postulate a massive halo of dark matter surrounds every cluster of galaxies	postulate clusters of galaxies are embedded in an energy scale variation
Gravitational Lensing Lensing by clusters of galaxies does not agree with observed mass	postulate a massive halo of dark matter surrounds every cluster of galaxies	postulate clusters of galaxies are embedded in an energy scale variation
Cluster Collisions Collisions between clusters separates dark matter from the hot gas	postulate the massive haloes of dark matter pass straight through the collision and stay with the galaxies	postulate energy scale variations pass straight through collision and stay with the galaxies
Cosmic microwave background Dark matter required to explain the power spectrum	dark matter clumped together early on and formed gravitational wells for the normal matter	energy scale variations existed early on and acted as gravitational wells for normal matter
Physical Cosmology Several problems require dark matter to explain: nucleosynthesis; age of Universe; CMB fluctuations; flat Universe	dark matter provided the extra energy density needed	variations in the energy scale effectively provided the extra density needed
Growth of Structure Universe has insufficient normal matter to account for the growth of structure	dark matter provides the gravitational wells needed for structures to grow	energy scale variations provide the gravitational wells needed for structures to grow

6.2 Both dark matter and energy scale variations are hypothetical. No dark matter particle has ever been detected and no variations in the energy scale have been positively identified.

7 Model Dependency

7.1 The following table summarises which observations are dependent on computer models.

Observation	Dark Matter	Energy Scale Variations
Spiral Galaxies Rotation curves	Newton's law of gravity	Newton's law of gravity
Galaxy Clusters High velocities of galaxies	Newton's law of gravity	Newton's law of gravity
Gravitational Lensing	Einstein's general theory of relativity	Einstein's general theory of relativity
Cluster Collisions	Newton's law of gravity	Newton's law of gravity
Cosmic microwave background power spectrum	complex computer model	complex computer model, not yet available
Physical Cosmology	ΛCDM model of the evolution of the Universe	complex computer model, not yet available
Growth of Structure	ΛCDM model of the evolution of the Universe	complex computer model, not yet available

7.2 The first four observations can be explained in a straightforward manner, by the direct application of either Newton's law of gravity or Einstein's general theory of relativity. The observational data can be displayed and we can "see" how the explanations work.

7.3 The last three observations are explained by somewhat complex computer models. We should have faith that they work for the dark matter hypothesis. Nevertheless with many computer models what you get out is to a large extent determined by what you put in. At the moment there are no computer models based on our conjecture of energy scale variations; the best we have is positive support from simple calculations. A lot more work is required here.

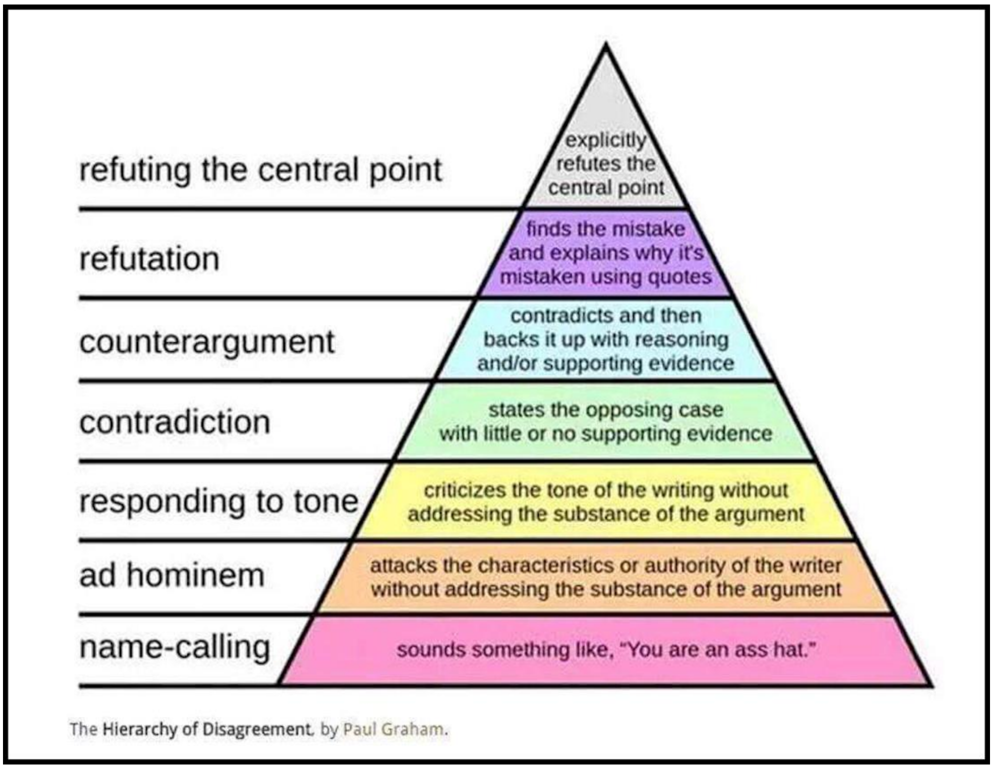


Figure 25.2. Paul Graham's hierarchy of disagreement. Our conjecture of energy scale variations sits at level 4 "counterargument" or level 5 "refutation".

8 Disagreement

8.1 Paul Graham has put forward a hierarchy for disagreement, going from level 0 "name-calling" to level 6 "refuting the central point". This is illustrated in Figure 25.2.

8.2 Dark matter is the argument or proposition that we disagree with. It is clear our conjecture that the energy scale varies from location to location puts us at least on level 4 "counterargument" if not on level 5 "refutation".

8.3 We have put forward an alternative to dark matter, namely energy scale variations; this is the counterargument. We have backed this up with a lot of reasoning and supporting evidence. But we have yet to find the knock-out blow to dark matter and we cannot deliver a complete refutation at this time. So we are at least at level 4 in the disagreement hierarchy "counterargument"|.

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Predictions

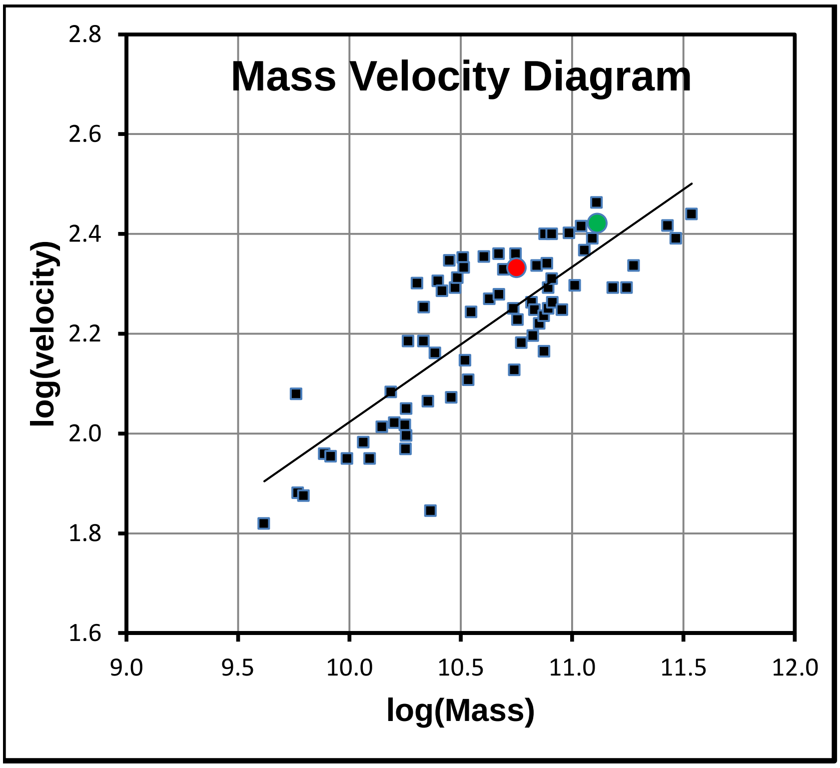

Figure 26.1: The mass vs velocity diagram for 74 spiral galaxies used in chapter "18: Galaxy Rotation Curves". The line has a slope of 0.3. The red dot is the Milky Way; the green dot is the Andromeda galaxy. This diagram is essentially the well-known Tully-Fisher relationship.

We look at some predictions that answer the question "if our conjecture is correct then what predictions can be used to test it?"

1 No dark matter particles will ever be detected

1.1 The presumption of this book is that dark matter does not exist. In its place we have the conjecture that the energy scale can vary from location to location. All scenarios where dark matter is invoked can be explained instead by variations in the energy scale.

1.2 It is very hard to prove a negative. So, although we are clear that dark matter is not required to explain observations, it is not possible to demonstrate that a small amount of something that can be labelled as dark matter does not exist.

1.3 If, as is assumed throughout this book, dark matter does not exist then there are no dark matter particles to detect. So no experiment will ever detect any dark matter particles. This includes accelerators used by particle physicists, such as the Large Hadron Collider. Dark matter particles do not exist so there is nothing to detect.

1.4 This is not particularly useful as a prediction simply because it is very hard to prove a negative. The argument goes that if we haven't found any dark matter particles yet then perhaps we have not carried out the correct experiment or are looking in the wrong place.

2 Dark Matter objects will never be detected

2.1 As dark matter does not exist it follows that no dark matter objects will ever be detected. So no planets made of dark matter; no stars made of dark matter; no galaxies made of dark matter; no objects anywhere made of nothing but dark matter.

2.2 In a sense this is a trivial prediction as it follows inevitably from prediction 1.

2.3 We have plenty of objects made of normal matter that do not contain any dark matter. You only have to look at the planets and the stars. Conversely, if dark matter exists, one might expect objects made solely from dark matter to exist. But dark matter doesn't exist and neither do any dark matter objects.

2.4 Again, as with Prediction 1, this is unhelpful as a prediction. If no dark matter object is ever found then we may have been looking in the wrong places.

3 Galaxies with little or no dark matter can exist

3.1 The standard model of cosmology, the ΛCDM model, argues that galaxies are formed when normal matter falls into gravitation potential wells of dark matter. This means all galaxies should have a substantial dark matter halo and that galaxies with little or no dark matter should not exist.

3.2 The work on the rotation curves of spiral galaxies shows that the energy scale variations are not all the same and that they come in a range of sizes. In terms of the Gaussian profiles employed there are two parameters: the height of the Gaussian; the 1/e-width of the Gaussian. Both appear to vary both randomly and independently of one another.

3.3 The variation in the Gaussian profiles for the energy scale variations means that some galaxies will show a large energy scale variation and others a much smaller one. So there is no problem in explaining spiral galaxies that appear to have hardly any dark matter; these are simply galaxies with a weak energy scale variation. Similarly there is no problem in explaining galaxies that appear to have an excessively large amount of dark matter. These simply lie in a strong energy scale variation.

3.4 A useful exercise would be to examine the distribution of the parameters that define the presumed Gaussian shape of our energy scale variations. They may have a normal distribution or some other shape.

3.5 This prediction cannot substantiate the existence of energy scale variations; it can only support their existence. However, it can possibly rule out alternative explanations for dark matter.

4 Local phenomena do not need dark matter

4.1 Our solution of energy scale variations works because the gravitational source and target are in different locations where the energy scale can have different values. By definition, where the source and target are in the same location the energy scale has a single value, and all observations should be explainable without the need for any extra gravitational force, i.e. dark matter. This applies to objects or regions close to one another, such as the solar system; binary stars; the centres of galaxies.

4.2 By local we mean that the separation between source and target is small compared to the 1/e-width of the energy scale variation. For example: the width of the energy scale variation for our galaxy is around 9 kpc ($\sim 3.5 \times 10^{21}$ m), whereas the size of our solar system is around 60 AU ($\sim 9 \times 10^{12}$ m); so a difference of at least 8 orders or magnitude. Hence it is unlikely that we could detect any changes across our solar system arising from a galactic energy scale variation.

4.3 We should stress the point made in section 4.1 above, that no dark matter is needed in the centre of galaxies. The ΛCDM model has a problem as it predicts a peak in the the density of the dark matter halo in the galaxy centres. This is contrary to observations. On the other hand our conjecture predicts no mass discrepancy in galaxy centres; there is no requirement for any extra mass and the observed mass should be sufficient to explain all observations there.

4.4 This is another negative prediction, so not particularly useful.

5 Galaxy clusters should disperse after collisions

5.1 Most of the normal matter in a cluster of galaxies is in the gas; the galaxies themselves are just a small fraction of the total. In collisions between galaxy clusters the gas appears to get stripped out whilst the galaxies simply pass through and carry on their way. This was discussed previously in chapter "21: Collisions between Clusters of Galaxies".

5.2 In the dark matter scenario the dark matter is not affected by the collision and continues with the galaxies. This means the dominating dark matter is still in place and should be strong enough to hold the galaxies together; the cluster should not disperse.

5.3 In the energy scale variation scenario the cluster loses most of its mass when the gas is stripped out. On their own the galaxies should be insufficient to hold the clusters together.

5.4 A virial theorem analysis of the clusters should show that they are breaking up and dispersing; i.e. that the kinetic energy in the galaxies, as derived from their velocities, should be more than twice the potential energy, as derived from weak gravitational lensing.

5.5 We might expect this to be a relatively straightforward piece of research but I am not aware that this analysis has taken place. This would clearly discriminate between the dark matter hypothesis and our energy scale variation conjecture.

6 Galaxy rotation curves eventually decline following Newtonian gravity

6.1 We discussed galaxy rotation curves in chapter "18: Galaxy Rotation Curves". Figure 18.2 shows that all rotation curves are expected to start declining at distances beyond twice the 1/e-width of the energy scale variation.

6.2 The rotation curves should decline following Newtonian gravity with the dependence of

$$\boldsymbol{v(r)} \;=\; \sqrt{\boldsymbol{G\,M\,(1+\gamma)}}\;\frac{\boldsymbol{1}}{\sqrt{\boldsymbol{r}}} \qquad (27.1)$$

where $\boldsymbol{v(r)}$ is the rotation speed; $\boldsymbol{M}$ the mass of the galaxy; $\boldsymbol{\gamma = B/A}$ the ratio of the height to the background level of the energy scale variation; $\boldsymbol{r}$ the radial distance.

6.3 Many of the rotation curves shown in Figures 18.6 and 18.7 of chapter "18: Galaxy Rotation Curves" do begin to show a fall off at large distances, exactly as our conjecture predicts. However, they do not extend far enough to confirm a $\boldsymbol{1/\sqrt{r}}$ fall off in the velocity.

6.4 To confirm this prediction we need observations of rotation curves out to large distances from the galaxy centre. By large we mean 3 or 4 times the 1/e-width of our energy scale Gaussian. In practical terms this means a distance of at least 40 kpc. Such observations are extremely difficult to obtain, but should be possible using the latest generation of radio telescopes.

7 Galaxy rotation curves

7.1 Figure 27.2 illustrates the expected shapes of galaxy rotation curves for a central mass. The curves are normalised so that the rotation speed is 1.0 at distance 1.0. The solid green line is the expected curve for normal Newtonian gravity; the fall off is proportional to $\boldsymbol{1/\sqrt{r}}$.

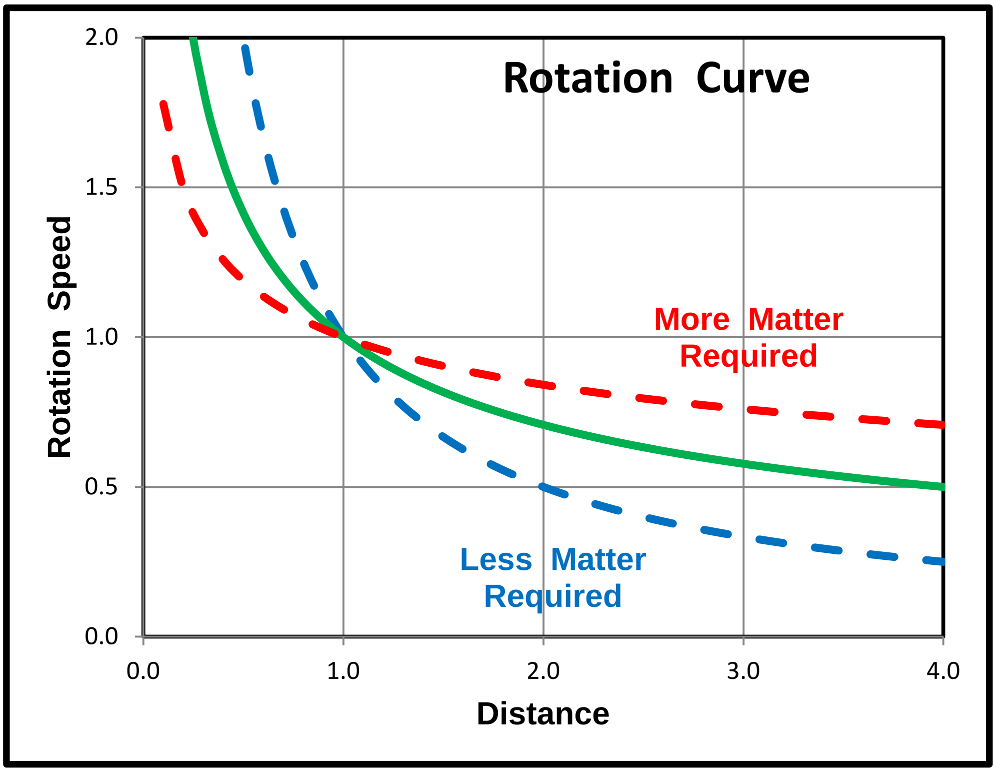

Figure 27.2: Illustration of galaxy rotation curves.

7.2 If the observed rotation curve lies above the green line, beyond distance 1.0, then additional matter is required. This is illustrated by the dashed red line. This is the usual situation for spiral galaxies and the usual explanation is that the galaxy is surrounded by a large halo of dark matter, which provides the extra mass.

7.3 Our explanation for such curves is that the galaxy lies in an energy scale variation. An energy scale variation that peaks at the galaxy centre and monotonically falls off will give rise to rotation curves in this part of the diagram.

7.4 If the observed curve lies below the green line then less matter is required. This is illustrated by the dashed blue line. For normal matter and dark matter this situation is impossible. You cannot have galaxy with a certain total mass inside some distance but with less total mass inside a distance further out.

7.5 Such curves can exist with energy scale variations. If, instead of continuously falling, the energy scale levels off or rises then the rotation speed will decrease faster than normal Newtonian gravity.

7.6 Observations should be made of spiral galaxies to see if any rotation curves show a faster decrease than the expected $\mathbf{1/\sqrt{r}}$.

8 Summary

8.1 We make the following seven predictions as a means of testing the idea of energy scale variations.

1. No dark matter particle will ever be detected.
2. No objects (planets, stars, galaxies) made entirely of dark matter will ever be found.
3. Galaxies containing little or no dark matter are perfectly possible.
4. No phenomena will be found where the gravitational effects of objects close to one another require the existence of dark matter. In particular no dark matter is required in the galaxy centres.
5. Galaxy clusters involved in collisions should show signs of break up, with the individual galaxies dispersing.
6. The rotation curves of spiral galaxies will show the expected $\mathbf{1/\sqrt{r}}$ at large distances.
7. Rotation curves showing there is too much mass present are possible and may even occur.

8.2 Predictions 1 to 4 are not very helpful as they predict situations that should not occur. Predictions 5 and 6 are much better as they make suggestions that can be tested against observations.

27
Problems

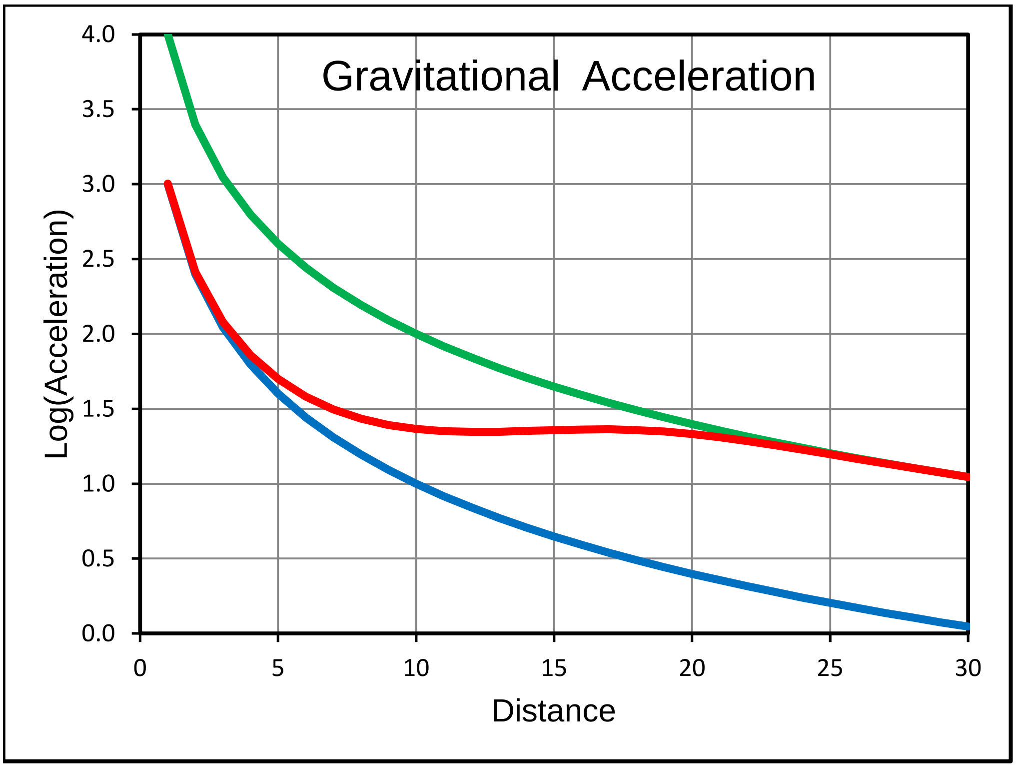

Figure 27.1. The variation of the gravitational acceleration with distance for a central point mass. The upper green curve shows the Newtonian gravitational acceleration for a high mass of M=10; the lower blue curve is the Newtonian gravitational acceleration for a low mass of M=1. The middle red curve is for an Energy Scale Variation that matches the green curve at large distances and matches the blue curve at small distances.

We look at some of the issues that remain with our idea of energy scale variations and ask the question "what bits need tidying up?"

1 Introduction

1.1 We have looked at the conjecture that the energy scale can vary from location to location. We have seen how this conjecture can explain all the observations and situations where dark matter is currently invoked.

1.2 No new idea is ever put forward without there being some problems with it, without there being some cases it does not explain, and without there being some technical or theoretical difficulties. Of course, I am convinced that our conjecture is correct and that the few problems I am aware of will get fixed. Needless to say I am working on these.

1.3 It is really bad practice to show only the cases that support an idea and deliberately to hide the cases that cause trouble. I do not believe there are any cases or considerations that kill outright our conjecture of energy scale variations. Nevertheless, I do have a number of minor concerns and the following sections look at these.

1.4 Figure 27.1 above is another illustration of how our conjecture of energy scale variations works for the rotation curve of spiral galaxies. It shows the gravitational acceleration for two bodies of mass 1.0 (blue curve) and 10.0 (green curve). The red curve is the acceleration for an energy scale variation and shows the way it "interpolates" between two Newtonian curves.

2 No Definite Detection

2.1 No energy scale variation has ever been detected as such. This is hardly surprising as variations in the energy scale are a new idea and nobody has looked for them. There are no observations that can only be explained through their existence. Dark matter is currently in a similar position in that no dark matter particle has ever been detected, despite the large number of experiments carried out over the past few decades.

2.2 One way out of this problem is to make predictions where the effects of energy scale variations are different from those of dark matter. Observations or experiments can then be made to confirm or deny the predictions. Some predictions are set out in chapter "26: Predictions".

2.3 Another way out of this problem is to create an energy scale variation. At the moment we have no idea how we might do this. And if energy scale variations are anything like black holes then building one may be really difficult or really dangerous.

3 No Theory

3.1 We do not have a theory for energy scale variations. We have postulated that they exist and seen how they can explain a large number of observations. So we have a physical model that fits the observations. This is a very good start but it cannot be the end of the story.

3.2 Most physics theories are field theories; e.g. we have electric and magnetic fields in the theory of electromagnetism. So perhaps we can introduce a scalar field, which defines the value of the energy scale at every point in space. I know my maths and physics are not strong enough to cope with the technical challenges of pursuing this, such as the scalar-tensor theories of gravity.

3.3 If we introduce a scalar field that describes variations in the energy scale then we are in the territory of scalar-tensor theories of gravity. This may be the way we have to go. But, at the moment. I do not know if this route is inevitable and I am somewhat unhappy in following this line of reasoning.

3.4 Not having a theory for energy scale variations affects how we tackle the ongoing difficulties. We know how energy scale variations behave and how they affect gravitational interactions. We can also surmise that at the end of inflation energy scale variations existed with random sizes in exactly the same way as the fluctuations in temperature and density.

3.5 We do not have a theory for how energy scale variations interact with one another. This is needed as an input into the computer models for the evolution of the Universe. For the density and temperature fluctuations we have the laws of physics so we can simply plug gravity and the other laws into our computer model, let it go, and see how the Universe evolves. We cannot do that, at the moment, for the equivalent fluctuations in the energy scale.

4 Lagrangian and Action

4.1 Most modern theories of physics are formulated in terms of Lagrangian mechanics and the principle of least action. We can go some way to following this path for the rotation curves of spiral galaxies.

4.2 The Lagrangian is the difference between the kinetic energy and the potential energy; we know both of these for our energy scale variations. The principle of least action leads to an equation involving the Lagrangian. We can input our energy scale variations into the Lagrange equation. The output is the equation for the rotation curve of spiral galaxies.

4.3 When we do this we get exactly the equation we have been using for the rotation curves of spiral galaxies. So, to a somewhat limited degree, our idea of energy scale variations is compatible with the principle of least action. This is discussed in greater technical detail at **www.varensca.com**.

5 Unknown Shape

5.1 We do not know what the shape of an energy scale variation we should adopt, nor what factors determine its behaviour. This is not surprising as we do not have a theory for energy scale variations. Such a theory would be expected to contain rules (laws) that govern the shape amongst other parameters.

5.2 The shape we have adopted throughout this book is the simple Gaussian; peaked at the centre and falling exponentially to some positive background level. Our Gaussian profiles have all been smooth although in reality this is not expected to be the case. We only have to look at the images of spiral galaxies to see that their disks are broken into spiral arms, and these are made up of discontinuous clumps of gas and stars. They are not at all smooth and it is somewhat remarkable that our simple smooth Gaussian models reproduce the rotation curves so well.

5.3 We should be able to make some progress using the rotation curves of spiral galaxies. Up to now we have fitted the rotation curve by choosing the density distribution and the energy scale variation. But we know the density distribution from the light emitted by the galaxy and the mass-to-light ratio for different types of star. So, in principle, we can invert the problem and derive the shape of the energy scale variation from the rotation curve and the density distribution.

6 Breaks the ΛCDM Model

6.1 The ΛCDM cosmological model (Λ cosmological constant + cold dark matter) is the standard cosmological model, sometimes referred to as the concordance cosmology model. It is our best model for explaining the history and properties of our Universe on a large scale.

6.2 Our conjecture that dark matter does not exist means there is no cold dark matter and by extension that the ΛCDM model is wrong. This is a serious step to take especially when we don't have a complete replacement to put in its place.

6.3 It may well be that researchers will want to restrict the idea of energy scale variations to just galaxy rotation curves, as an alternative to MOND (see later). They will not want to entertain the prospect of having to replace the ΛCDM model.

7 No Computer Models

7.1 There are no computer models for the evolution of the Universe based on energy scale variations. Computer models do exist for dark matter, notably the ΛCDM model. It would be helpful to have an Energy Scale Variation model (ESV model) for the Universe.

7.2 It is not possible, of course, to write computer code without a theory for energy scale variations, and without details on their shapes and on what rules govern their creation and evolution.

7.3 Hopefully the ESV model will get written and the computations carried out. These will enable us to see what fluctuations arise in the cosmic microwave background, and to see how structures arise and evolve.

8 Summary

8.1 There has been no definite detection of a variation in the energy scale.

8.2 There is no theory for energy scale variations.

8.3 The shape of energy scale variations is unknown.

8.4 Our conjecture of energy scale variations breaks the ΛCDM model of cosmology.

8.5 No computer models for the evolution of a Universe containing energy scale variations exist.

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Alternatives to Dark Matter

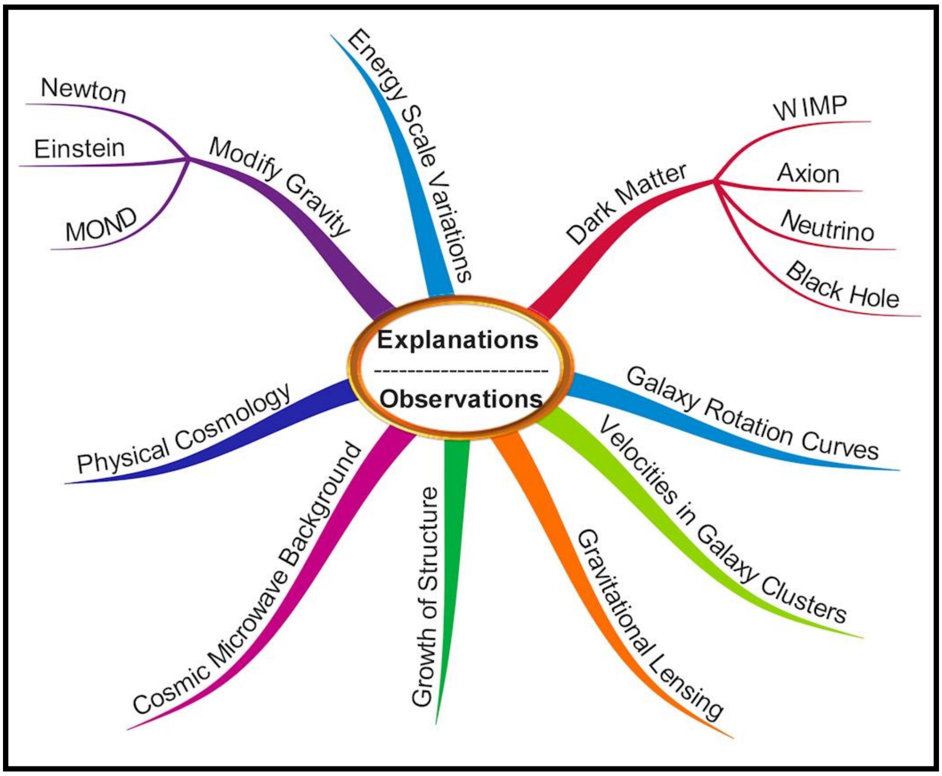

Figure 28.1. Lower half shows areas where observation have problems with gravity. Upper half shows suggested explanation.

We answer the question "what other suggestions are there for dark matter?"

1 Introduction

1.1 Throughout this book we have been looking at the areas where astronomical observations cannot be understood in terms of Newton's law of gravity (or Einstein's general theory of relativity). These are illustrated by the bottom half of Figure 28.1. Apart from our new conjecture there are only two possible explanations and these are illustrated in the top half of Figure 28.1.

1.2 The first way is by postulating the existence of dark matter, and we spent the majority of this book covering this. Many explanations assume dark matter is some sort of particle and we could have spent time of discussing the various options. However, our primary concern has been on the idea of dark matter and not on its nature.

1.3 The second way is to change the way gravity works. So far we have taken it that Newton's law of gravity is correct and fully applicable for the regimes we are working in without any changes. We now look at a couple of ideas for how gravity might work differently from what we are accustomed.

2 General Relativity

2.1 The general theory of relativity is Einstein's theory of gravity. In this theory gravity arises from the curvature of space-time, which itself arises from the mass energy present. General relativity is extremely successful at explaining a wide range of phenomena, including the expansion of the Universe and gravitational lensing. The difficulty in trying to modify general relativity is finding a way that explains dark matter without breaking its ability to explain all the other phenomena.

2.2 Dark matter is generally accepted to be a particle, which means it has to be represented by a field. It is extremely difficult to introduce additional fields into general relativity because the mathematics is very challenging. A new field can be a scalar field, a vector field, or a tensor field; all come with their own set of problems.

2.3 The recent detection of gravitational waves has shown that gravity travels at the speed of light. This fact has already ruled out many of the attempts to modify general relativity simply because these predict that gravity should travel at a speed different from that of light.

2.4 The current position is that Einstein's original formulation of general relativity continues to pass all the tests that are thrown at it. The only modification that is widely accepted is the addition of the cosmological constant as a means of explaining dark energy and the apparent accelerated expansion of the Universe.

2.5 Although some modifications to general relativity are still being pursued they can only make progress if they come up with predictions that can be tested. At the moment it seems unlikely that any change made to general relativity will explain dark matter. However, the longer that dark matter particles remain undetected, or some other solution comes along, the greater the incentive to keep on trying to modify general relativity.

3 MOND

3.1 MOND is the acronym for MOdified Newtonian Dynamics; it is the brain-child of Mordehai Milgrom who proposed the idea in 1983.

3.2 MOND works with acceleration and postulates that Newton's law of gravity changes at very low accelerations. At very weak accelerations gravity depends on the inverse of the distance rather than on the inverse square of the distance, see Table 28.1.

3.3 The acceleration, $\boldsymbol{a}$, under MOND is given by dividing the Newtonian acceleration by a so-called interpolation function. Mathematically this can be written as

$$\boldsymbol{a} = \boldsymbol{a_N} / \boldsymbol{\mu}\left\{\frac{\boldsymbol{a}}{\boldsymbol{a_0}}\right\} \tag{28.1}$$

where $\boldsymbol{a_N}$ is the normal Newtonian acceleration; $\boldsymbol{a_0}$ is the MOND standard acceleration; $\boldsymbol{\mu}\left\{\frac{\boldsymbol{a}}{\boldsymbol{a_0}}\right\}$ is the interpolation function.

3.4 The interpolation function, $\boldsymbol{\mu}$, is constrained by

$$\boldsymbol{\mu}\left\{\frac{\boldsymbol{a}}{\boldsymbol{a_0}}\right\} = \mathbf{1} \tag{28.2}$$

when $\boldsymbol{a} \gg \boldsymbol{a_0}$, i.e. in the inner part of the galaxy. In this case we are back with normal Newtonian gravity.

And by

$$\boldsymbol{\mu}\left\{\frac{\boldsymbol{a}}{\boldsymbol{a_0}}\right\} = \frac{\boldsymbol{a}}{\boldsymbol{a_0}} \tag{28.3}$$

when $\boldsymbol{a} \ll \boldsymbol{a_0}$, i.e. in the outer part of the galaxy. In this case gravity depends on the inverse of the distance.

3.5 In the inner region of a galaxy, where the gravitational acceleration is much greater than the MOND acceleration, all three models are the same. So there is no way to separate MOND from Newton or from our energy scale variations. All predict exactly the same behaviour as can be seen in Table 28.1.

3.6 It is in the outer region of a galaxy, where the acceleration is much less than the MOND standard acceleration, that functional differences between the models appear. The behaviour of our energy scale variation model matches Newtonian gravity, with the acceleration depending on the inverse square of the distance.

3.7 MOND, however, has a different functional form as is clear from the bottom right cell in Table 28.1. The acceleration depends on the inverse distance, rather than the inverse square distance. And, importantly, the velocity is constant and so gives rise to a flat rotation curve.

3.8 The differences between Newton, our energy scale variations, and MOND are summarised in the following table. $\boldsymbol{a}$ is the acceleration; $\boldsymbol{v}$ is the rotational velocity

	Newton	Energy Scale	MOND
General	$a = a_N = \frac{G\,M}{r^2}$	$a = a_N \frac{\xi(0)}{\xi(r)}$	$a = a_N/\mu\left\{\frac{a}{a_0}\right\}$
Inner galaxy $a \gg a_0$	$a = \frac{G\,M}{r^2}$ $v^2 = \frac{G\,M}{r}$	$a = \frac{G\,M}{r^2}$ $v^2 = \frac{G\,M}{r}$	$a = \frac{G\,M}{r^2}$ $v^2 = \frac{G\,M}{r}$
Outer galaxy $a \ll a_0$	$a = \frac{G\,M}{r^2}$ $v^2 = \frac{G\,M}{r}$	$a = \frac{G\,M\,(1+\beta)}{r^2}$ $v^2 = \frac{G\,M(1+\beta)}{r}$	$a = \frac{\sqrt{G\,M\,a_0}}{r}$ $v^2 = \sqrt{G\,M\,a_0}$

Table 28.1. The algebraic expressions for various quantities for (a) Newtonian gravity, (b) energy scale variations, and (c) MOND.

3.9 When it comes to fitting actual rotation curves there is no doubt that MOND does a good job, much better than dark matter. MOND is probably on a par with the fitting we get with our conjecture of energy scale variations.

3.10 At first glance it may seem that MOND is similar to our conjecture of energy scale variations. MOND has its μ function and we have our ξ function. But conceptually the two theories are completely different. And the behaviours at large distances from the galaxy centre are also completely different. MOND predicts the rotation curves remain flat at greater and greater distances, whereas our conjecture predicts the curves revert to a Newtonian-like fall off.

3.11 Although MOND is very successful with the rotation curves of spiral galaxies it is much less successful with the other areas, such as gravitational lensing. The vast majority of scientists do not accept any part of MOND, they prefer to stick with dark matter. So MOND is very much a minority interest.

29

Other Considerations

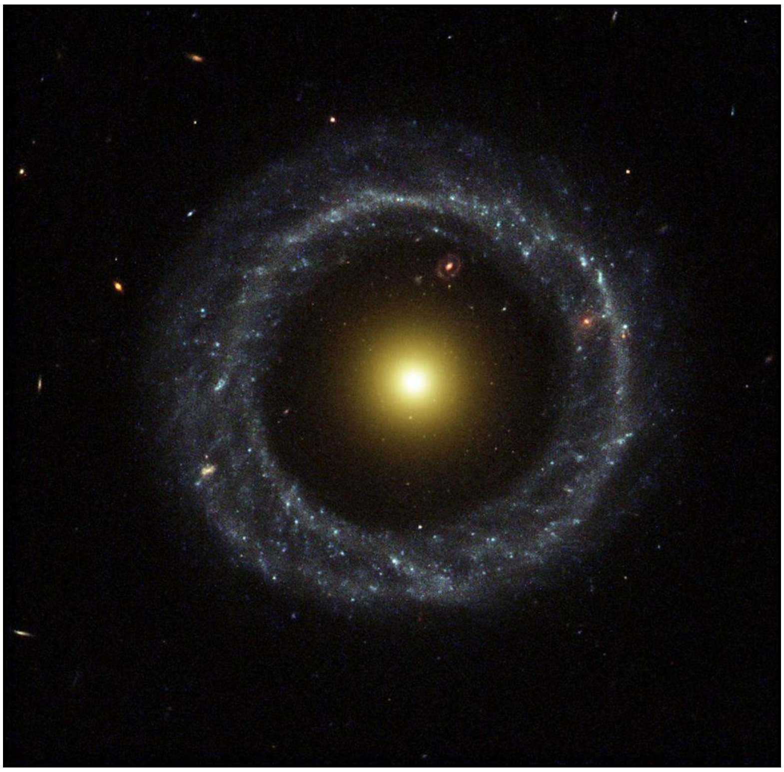

Figure 29.1. Hoag's Object, a galaxy with a detached ring of stars and gas. (Image credit: Hubble image. NASA and The Hubble Heritage Team STScI/AURA; Acknowledgment: Ray A. Lucas STScI/AURA)

We look at a number of places where dark matter is not invoked and answer the question "how does our conjecture throw new light on these astronomical situations?"

1 Hoag's Object

1.1 Figure 29.1 shows the Hubble image of Hoag's object, a ring galaxy discovered by Art Hoag in 1950. It has a central nucleus that is yellow in colour and made up of old stars. Detached from the nucleus is a wide ring that is blue in colour and made up of young stars.

1.2 Ring galaxies are thought to be formed when another galaxy passes through the disk of the galaxy; the ring being formed as a ripple effect. No second galaxy can be found near Hoag's object, which leaves the formation of the ring a puzzle.

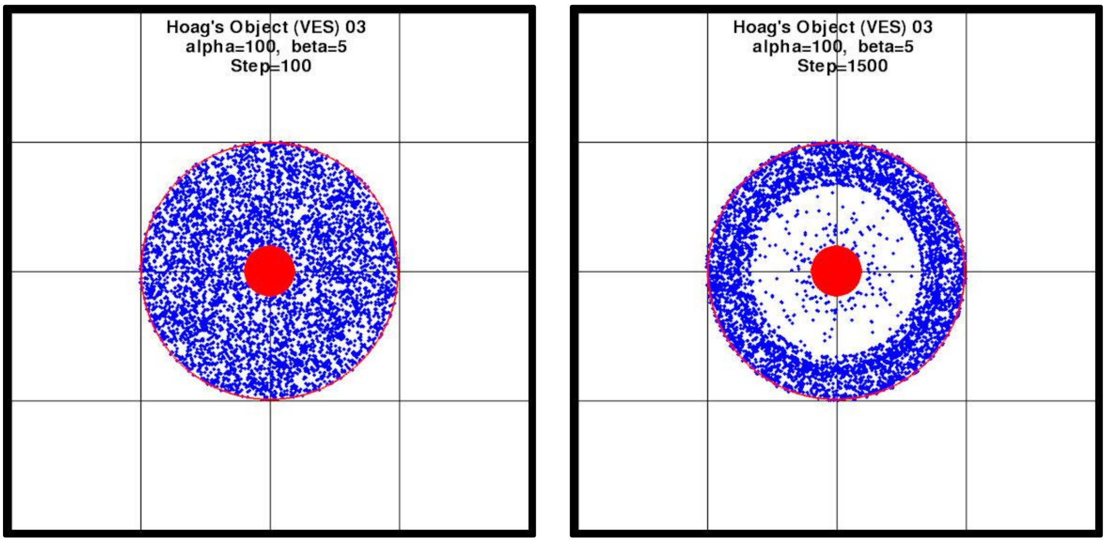

Figure 29.2. Simulation of a disk galaxy and the generation of a detached ring following a change in the energy scale variation.

1.3 So far in this book the energy scale variations have been taken to be fixed and unchanging. Here we make use of simple computer simulations to show what happens when an energy scale variation changes.

1.4 Figure 29.2 shows the effect on a disk galaxy when the width of the energy scale doubles in size and then returns to its original width. The left panel shows the starting position of a disk galaxy with a central condensation (red disk) and a disk of stars (blue dots). The right panel shows the position well after the changes to the energy scale variation have taken place. Once the ring is formed it appears to be stable and long lasting. The similarity with Hoag's Object is striking.

1.5 The ring is formed by the stars and gas moving outwards towards the edge of the galaxy, which hardly moves at all. The movement acts as a compression wave, which squeezes the gas and leads to a period of star formation. Hence we would expect the ring to contain a high proportion of young stars in comparison to the central region of old stars.

1.6 This work shows that a change in the energy scale variation can produce a ring galaxy without interaction with another second galaxy. However, some mechanism or instability is still needed to trigger the change.

2 Ring Galaxies and Shell Galaxies

2.1 Many spiral galaxies appear to have circular rings of stars amidst the spiral pattern. It is known that the spiral arms cannot be permanent features and that they probably arise through density waves. Any given spiral arm is not permanent but overall some form of spiral pattern is always present.

2.2 Other galaxies have a shell structure to their disks. The disks are made up of fragments of discontinuous shells. These are almost certainly the result of encounters with another galaxy. The galaxy has either passed straight through the disk or merged through a series of oscillating collisions.

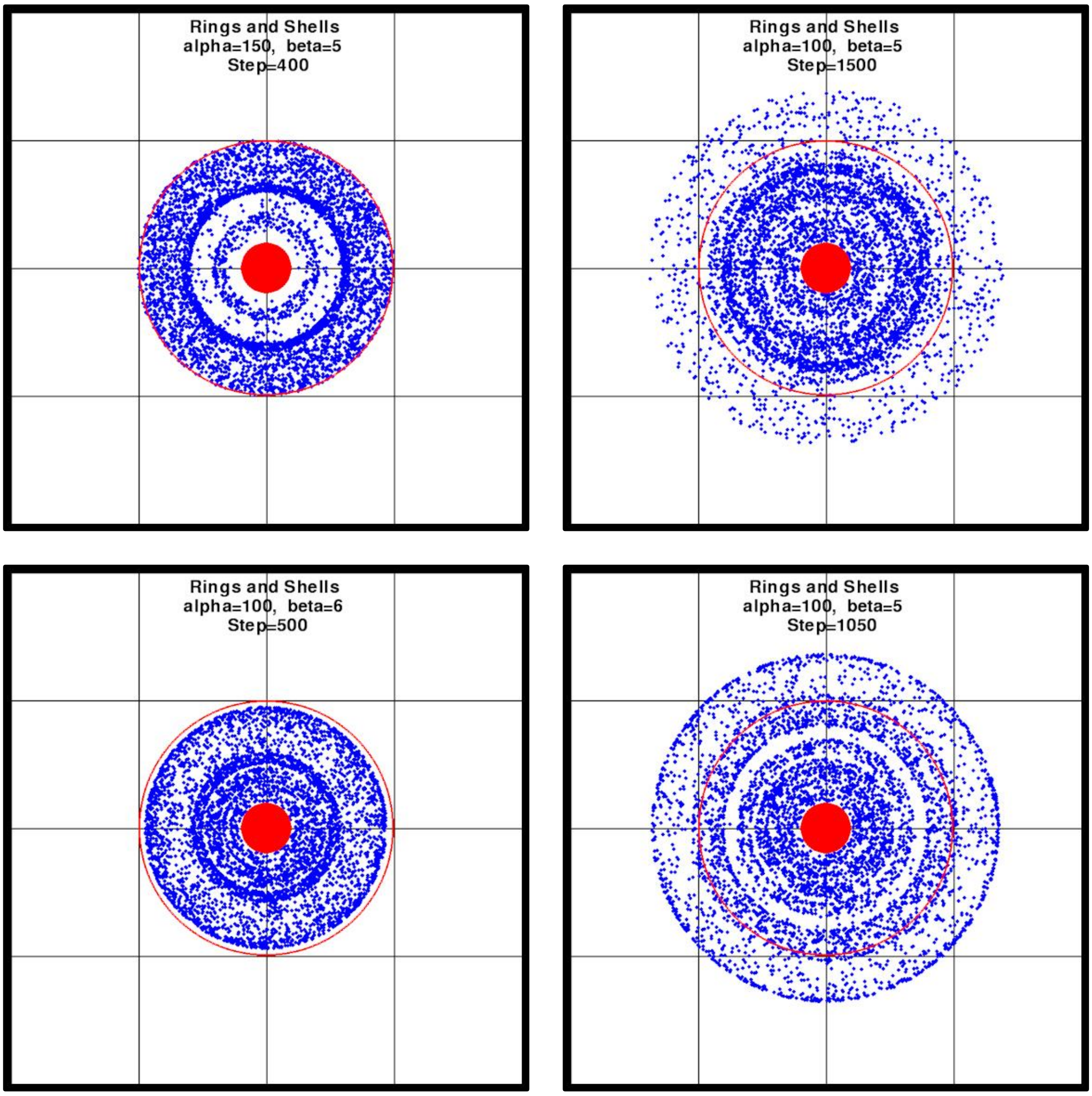

Figure 29.3. A selection of ring patterns that arise when the height or the width of the energy scale variation changes. If these changes occur in real galaxies then we may get short arcs rather than complete rings.

2.3 Lenticular galaxies, which are borderline between spiral and elliptical galaxies, have flat disks that often have multiple rings of dust. These are usually visible as concentric circles of dark dust against the bright stars.

2.4 Following on from section 1 above where we looked at Hoag's object we can examine what patterns arise when an energy scale variation changes. We have been using Gaussian-shaped variations that are characterised by a height and a width. We can see what happens when they change in different ways.

2.5 Figure 29.3 shows some patterns or rings and shells that result from different changes to the energy scale variation. The same computer simulation was used to generate the patterns, but with different sets of changes, either changing the width of the height.

2.6 It is clear that changes to the height or width of the energy scale variation do give rise to rings and shells of material in the disk of a galaxy. The trigger for the formation of rings and shells is undoubtedly through interaction with another galaxy. However, changes in the energy scale variation may also play a significant role.

3 Cosmic Voids

3.1 The large scale structure of the Universe appears to be foam-like in that it is made up of bubbles, walls, and filaments. Galaxies tend to lie on the surface of the bubbles, in the walls, and along the filaments. The insides of the bubbles are the voids where very few galaxies are found.

3.2 The formation of the voids is not fully understood and some models need dark energy to assist in the creation of voids.

3.3 Initially the matter in the Universe was made up of two distributions

(a) around 15% normal matter as random fluctuations about an average density, and

(b) around 85% dark matter as a second set of random fluctuations about its own average density.

The two distributions are added together. As dark matter is around six times more plentiful than normal matter it is the dark matter that controls how the Universe evolves. It is currently thought to be the low density regions of the dark matter that give rise to the voids.

3.4 For our conjecture of variations in the energy scale we again have two distributions

(a) the normal matter as random fluctuations about the average density, and

(b) the variations in the energy scale as random fluctuations about the average of the energy scale.

The gravitational influence is defined by multiplying the distributions together.

3.5 The matter in regions where the energy scale is below average will have a much diminished gravitational attraction. Very little matter will be attracted to them. Neighbouring regions with higher values of the energy scale have a stronger attraction and the matter in the low value regions naturally drifts away.

3.6 The nett effect is that large regions where the energy scale is below the average lose matter and on a cosmic scale these regions become voids. Within these regions there can be smaller regions with an above average value of the energy scale and galaxies can form there. So we expect some galaxies to exist within voids; voids should not be completely empty.

4 Dark Energy

4.1 This section on dark energy and the next section on inflation contain a few equations, which some of you may find a little difficult to follow. So I should perhaps have put them into chapter "30: Technical".

4.2 Dark energy is a hypothetical form of energy invoked to explain the apparent accelerated expansion of the Universe. It is completely different from dark matter. Dark matter is presumed to exist in astronomical objects where the additional gravitational force explains the rotation curves of spiral galaxies and the high velocities of galaxies in clusters. Dark energy does not affect individual objects but the whole of space-time.

4.3 Observations of type Ia supernovae in very distant galaxies show that they are around 20% fainter than expected. This demonstrates that the Universe is not slowing down, as had always been expected, but is in fact speeding up. The Universe is accelerating. Matter, including dark matter, can only cause the Universe to slow down. So this is where dark energy comes into play as its primary characteristic is having a repulsive effect that can cause the expansion of the Universe to accelerate.

4.4 In chapter "23: Physical Cosmology" we presented our version of the Friedmann equation for a homogeneous matter-only Universe. After the epoch of the cosmic microwave background radiation is unimportant and we can work with a Universe containing only matter. So just matter; no radiation, no dark matter, and no dark energy. For this the Friedmann equation is

$$\left(\frac{\dot{\boldsymbol{a}}}{\boldsymbol{a}}\right)^{2} = \boldsymbol{H}^{2} = \frac{8\,\pi\,G}{3\,c^{2}}\,\varepsilon_{B}\,\gamma \tag{29.1}$$

where $\boldsymbol{a}$ is the length scale factor; $\dot{\boldsymbol{a}}$ the rate of change of the scale factor; $\boldsymbol{H}$ the Hubble parameter; $\boldsymbol{\varepsilon_B}$ the energy density for normal baryonic matter; $\boldsymbol{\gamma}$ the strength of the energy scale variation.

4.5 This equation tells us that the square of the expansion speed is proportion to the energy density of normal matter and to our energy scale parameter.

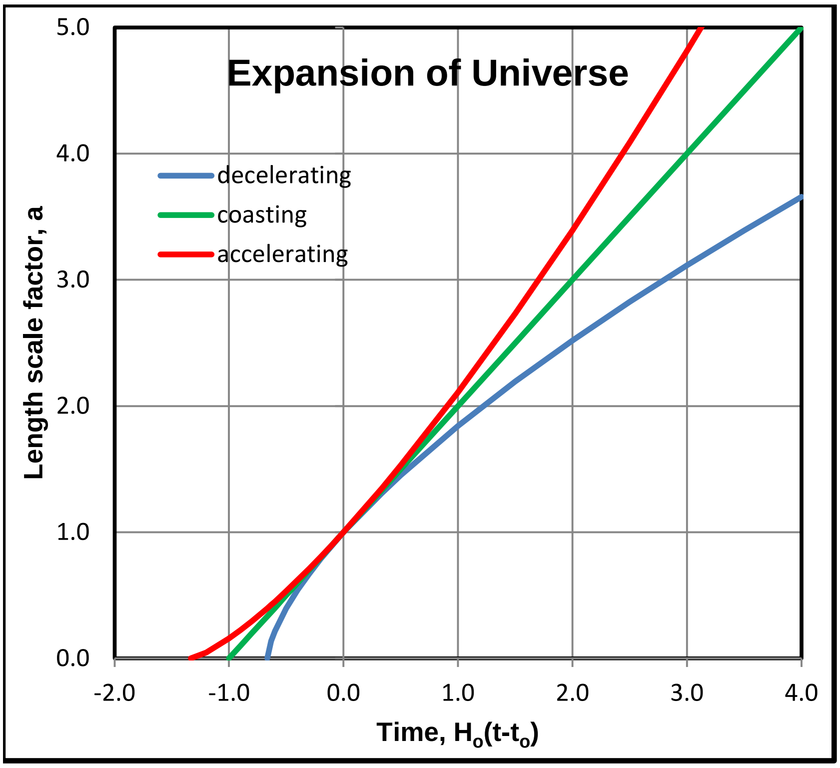

Figure 29.4. Graph showing the expansion of the Universe for different power laws of the energy scale parameter. The present time is indicated by Time 0.0 and Length scale 1.0. Until recently it was believed our Universe was coasting, as indicated by the green line. But it turns out that the Universe has started accelerating, as indicated by the red curve.

4.6 We can put in the known physics of normal baryonic matter and differentiate the Friedmann equation to get at the acceleration of the Universe. This is

$$\left(\frac{\ddot{a}}{a}\right) = -\frac{1}{2}\left(\frac{\dot{a}}{a}\right)\left\{\left(\frac{\dot{a}}{a}\right) - \left(\frac{\dot{\gamma}}{\gamma}\right)\right\} \tag{29.2}$$

4.7 Without the γ term the right-hand side of this equation is negative, which means the Universe is decelerating or slowing down. Most astronomers assumed this was how the Universe was behaving up until the observations of the type Ia supernovae.

4.8 By suitable choice of the way our energy scale parameter, γ, behaves we can make the right-hand side of equation (29.4) positive, which means the Universe is accelerating.

4.9 Figure 29.4 show how the Universe expands for three different power laws for how the energy scale varies with time. The blue curve is for a decelerating Universe, i.e. slowing down; there is no observational evidence for this. The green curve is for a coasting Universe, i.e. the acceleration is zero and the speed of expansion is constant. This is the curve everyone thought the Universe was following. The red curve is for an accelerating Universe; this is the curve we now think the Universe is following.

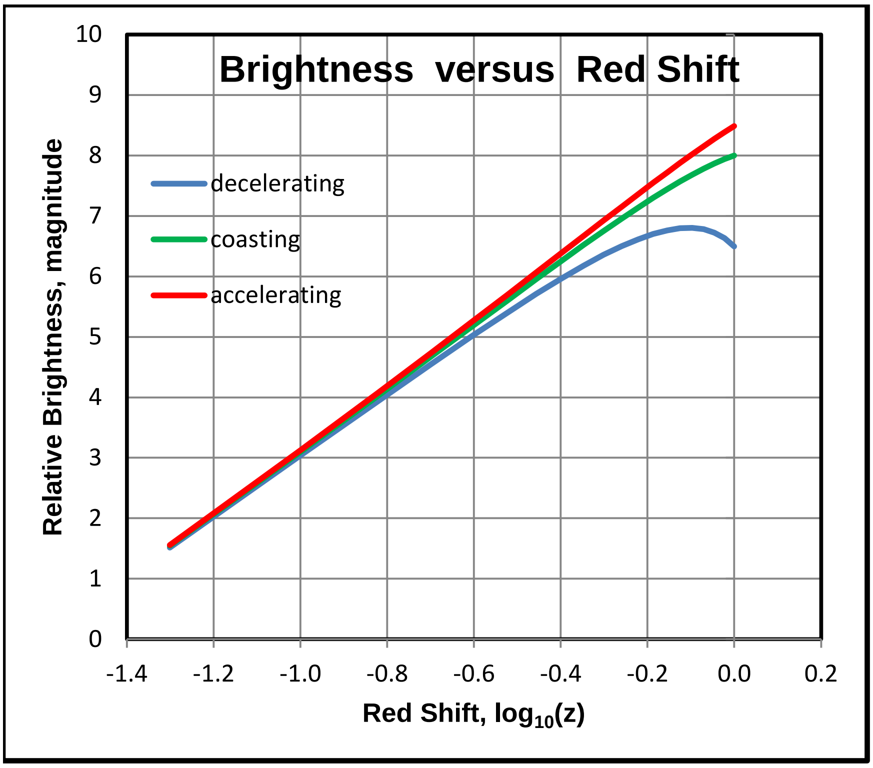

Figure 29.5. Graph showing the relative brightness of objects against red shift. Nearby objects have low red shift and lie on the left; remote objects have high red shift and lie on the right. Brighter objects have low magnitudes and lie towards the bottom; fainter objects have large magnitudes and lie towards the top. The remote type Ia supernovae would lie on the upper part of the red curve.

4.10 The calculations behind Figure 29.4 show that a suitable power law for the way the energy scale changes with time can give rise to an accelerating Universe. There is no need for any dark energy, and also no need for any dark matter.

4.11 In order to understand the results for type Ia supernovae we need a plot of brightness against red shift. Figure 29.5 does this for the same data as used in Figure 29.4. The blue line is for a decelerating Universe. The green line is for a coasting Universe. The red line is for an accelerating Universe.

4.12 Supernovae on the green line have the expected brightness. Supernovae below the green line, e.g. on the blue line, appear brighter than expected. Supernovae above the green line, e.g. on the red line, appear fainter than expected.

4.13 The red line in Figure 29.5 matches very closely the results for type Ia supernovae. These appear fainter than expected at high red shift. If the type Ia supernovae were plotted on Figure 29.5 then they would lie on the red line.

4.14 Figure 29.5 again shows that by suitable choice of the way the energy scale varies with time we can have an accelerating Universe where the type Ia supernovae appear fainter than expected at high red shift. No dark energy and no dark matter are required.

5 Inflation

5.1 Inflation is the period of rapid expansion at the beginning of the Universe when the size of the Universe is thought to have increased by at least 26 orders of magnitude in a tiny fraction of a second. We can look at this in a similar way to dark energy as covered in the previous section.

5.2 We assume during inflation the Universe contained only radiation; no matter; no dark matter; not dark energy. For this the Friedmann equation is

$$\left(\frac{\dot{a}}{a}\right)^2 = H^2 = \frac{8\,\pi\,G}{3\,c^2}\,\varepsilon_R\,\gamma \tag{29.3}$$

where a is the length scale factor; $\dot{a}$ the rate of change of the scale factor; H the Hubble parameter; ε_R the energy density for radiation; γ the strength of the energy scale variation.

5.3 This is exactly the same equation as we had for dark energy above, equation (29.1), with the exception that we now have the radiation energy density in place of that for normal matter.

5.4 We can put in the physics for radiation, do some maths, and get to the equation for the acceleration

$$\left(\frac{\ddot{a}}{a}\right) = -\frac{1}{2}\left(\frac{\dot{a}}{a}\right)\left\{2\left(\frac{\dot{a}}{a}\right) - \left(\frac{\dot{\gamma}}{\gamma}\right)\right\} \tag{29.4}$$

where $\ddot{a}$ is the acceleration of the scale factor, i.e. how fast the Universe is speeding up of slowing down. This equation is almost the same as that for dark energy, equation (29.2). This time we have a factor of 2 inside the braces; that's the difference between radiation and normal matter.

5.5 As with dark energy we can choose a power law for the behaviour of both the scale factor a and our energy scale parameter γ. A suitable choice of the power law means that the right-hand side of equation (29.4) is positive, which means the Universe is accelerating.

5.6 Standard models for inflation assume that it was a period of exponential expansion. For our solution we have a period of power law expansion. This is not quite as severe as exponential expansion but it can give the required expansion of 26 orders of magnitude. There are a number of adjustable parameters so we can make inflation happen within the first 10^{-32} s if we have to.

5.7 A lot more work needs to be carried out on this particular idea. For example: we need to understand how it would start and what would cause it to come to an end. All we want to do here is put down a marker that a change in the energy scale can get the job done.

6 The Electric Charge Scale

6.1 In this book we have restricted ourselves to the scales of length, time, and mass (or in our case energy). And we have also restricted ourselves to situations involving gravity, which can be considered to work by action at a distance.

6.2 When we look at the scale for electric charge we notice a number of similarities. The force between two charges is proportional to the product of the charges and inversely proportion to the square of the distance. The force can also to be considered to work by action at a distance.

6.3 Newton's law of gravity for the force between two masses can be written as

$$\boldsymbol{F = G\,\frac{m_1\,m_2}{r^2}} \tag{29.10}$$

Coulomb's law for the force between two electric charges can be written as

$$\boldsymbol{F = \frac{1}{4\pi\varepsilon_0}\,\frac{q_1\,q_2}{r^2}} \tag{29.11}$$

where $\boldsymbol{\varepsilon_0}$ is the permittivity of free space.
The similarities between the two equations are obvious.

6.4 We are not going to pursue this any further other than to put down a marker that perhaps we should examine situations where a change in the scale for electric charge between two regions might give rise to observable phenomena.

7 Recollapse

7.1 We should make a trivial point that has probably occurred to you already. If the background level of the energy scale becomes very small then the gravitational attraction can become arbitrarily large. If a region of space has become distended then it will recollapse should the background energy level drop far enough.

7.2 The shape of an energy scale variation is illustrated in Figure 17.3 of chapter "17: How It Works". This has a maximum height of **B** over a background level of **A**. We have already seen that the strength of the gravitational attraction on a target by a source depends on the ratio of the energy scale strengths of the source and target. This was shown in equation (17.2) in chapter 17.

7.3 We can increase the strength of the attraction either by increasing the height or by decreasing the background level. For the astronomical scenarios already discussed the ratio of source to target has been of order 10. Serious recollapse would start happening if this ratio took extreme values, say of order 1 million.

8 Summary

8.1 A change in the shape of an energy scale variation can give rise to a ring galaxy similar to Hoag's Object.

8.2 Changes to the height or the width of the energy scale variation can give rise to rings and shells in disk galaxies.

8.3 A negative variation in the energy scale would give rise to a region of space where the gravitational attraction of matter was diminished. Matter would tend to get pulled out of such region, which on a cosmic scale would end up as voids.

8.4 A suitable choice of the function describing the energy scale in the Friedmann equation, for a matter only Universe, can give rise to an accelerating Universe. A simple function results in a model that closely resembles the acceleration as mapped out by remote type Ia supernovae. This means that variations in the energy scale can reproduce the effects of dark energy.

8.5 A different choice for the function describing the energy scale in the Friedmann equation, for a radiation only Universe, gives rise to a Universe that expands with a power law. A simple function can explain how the Universe expanded by at least 27 orders of magnitude immediately after the Big Bang. This means that variations in the energy scale can potentially reproduce the effects of inflation.

8.6 The similarity between Newton's law of gravity between masses and Coulomb's law for electric charges suggests we should look for changes in the scale for electric charge.

8.7 If the background level of the energy scale drops far enough then distended or expanding objects may recollapse.

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Technical

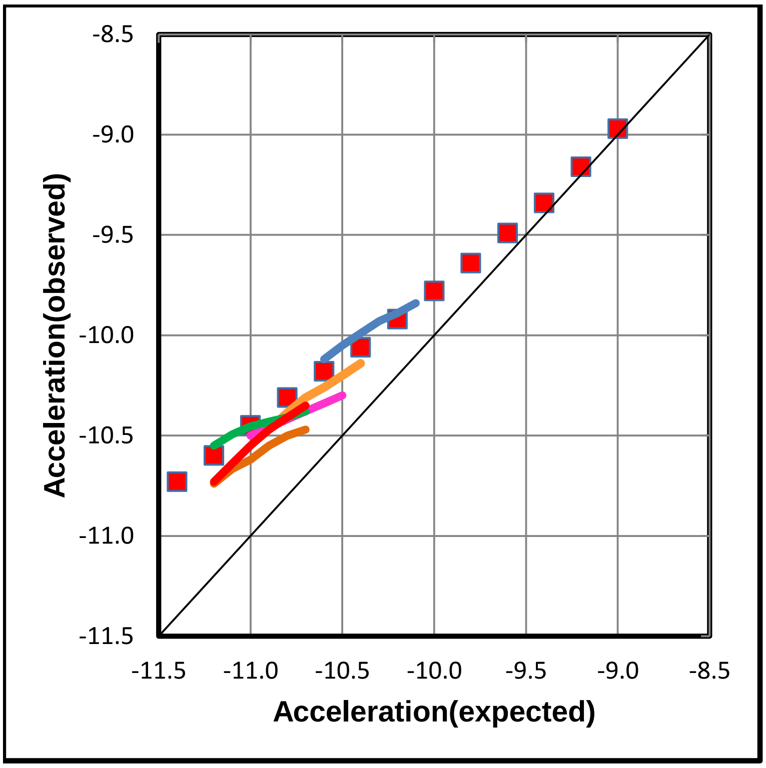

Figure 30.1: The radial acceleration relation. Spiral galaxies show a connection between the observed radial acceleration and that expected from the normal matter. This empirical relation is shown as the red squares. The coloured lines are the data for six galaxies following our conjecture.

We get our hands dirty by looking at a few equations that show how variations in the energy scale changes the way gravity works.

1 Introduction

1.1 The idea of this book was to present the idea of variations in the energy scale in an entirely descriptive manner; purely qualitative, not at all quantitative, and certainly no equations. Mostly the book adheres to this aspiration.

1.2 However, I have no doubt that many of you are very able mathematicians and scientists, and you probably demand more meat. The following sections set out some of my thoughts on energy scale variations in a more mathematical manner, so quite a few equations.

1.3 For those of you who want the full treatment there are approaching 20 scientific papers available as PDF files on web-site:

www.varensca.com

None of these have been peer-reviewed and none have been published in any journals.

1.4 An example of the content of one of these papers is shown in Figure 30.1 above. There is an empirical relation for spiral galaxies known as the radial acceleration relation where there is an observed connection between the radial acceleration and the distribution of normal matter. This is not what is expected because the radial acceleration should be determined principally by the dark matter and not by the normal matter. Figure 30.1 shows that our conjecture of energy scale variations is compatible with the observations.

2 No spooky action at a distance

2.1 Newtonian gravity operates instantaneously through the action-at-a-distance of a force that comes from a remote mass. Although the target of the force is local, the source of the force is remote.

2.2 Einstein's general relatively works through the local curvature of space-time that is produced by a remote mass and transmitted at the speed of light. So the force is local and the source of the force, the curvature of space-time, is also local.

2.3 We would like our conjecture of variations in the energy scale to operate locally. We don't want any spooky action at a distance.

2.4 For our energy scale variation the force, $\boldsymbol{F}$, on a local mass, $\boldsymbol{m}$, from a remote mass, $\boldsymbol{M}$, is

$$\boldsymbol{F}(\boldsymbol{r}) \;=\; -\,\frac{\boldsymbol{G}\,\boldsymbol{M}\,\boldsymbol{m}}{\boldsymbol{r}^2}\,\frac{\boldsymbol{\xi}(\boldsymbol{0})}{\boldsymbol{\xi}(\boldsymbol{r})} \tag{30.1}$$

where $\boldsymbol{\xi}(\boldsymbol{r})$ is the dimensionless function describing the energy scale variation.

2.5 This can be written as

$$\boldsymbol{F}(\boldsymbol{r}) \;=\; -\,\{\boldsymbol{G}\,\boldsymbol{M}\,\boldsymbol{\xi}(\boldsymbol{0})\}\left\{\frac{\boldsymbol{m}}{\boldsymbol{r}^2\;\boldsymbol{\xi}(\boldsymbol{r})}\right\} \tag{30.2}$$

The first term on the right hand side is fixed; the second term depends on local values only.

2.6 The force on mass, $\boldsymbol{m}$, at position $\boldsymbol{s}$ is

$$\boldsymbol{F}(\boldsymbol{s}) \;=\; -\{\boldsymbol{G}\,\boldsymbol{M}\,\boldsymbol{\xi}(\boldsymbol{0})\}\left\{\frac{\boldsymbol{m}}{\boldsymbol{s}^{2}\;\;\boldsymbol{\xi}(\boldsymbol{s})}\right\} \tag{30.3}$$

2.7 On comparing equations 30.2 and 30.3, we see that the first bracketed term is the same for all locations and is fixed. The second bracketed term depends only on locally measured values. So we argue that the gravitational force is determined by purely local values. This means energy scale variations satisfy our requirement for locality. There is no spooky action at a distance.

3 No Local Effects

3.1 Consider our star, mass m, going round the centre of our galaxy, mass M. The gravitational force is, as given in equation 30.1:

$$\boldsymbol{F}(\boldsymbol{r}) \;=\; -\,\frac{\boldsymbol{G}\,\boldsymbol{M}\,\boldsymbol{m}}{\boldsymbol{r}^{2}}\,\frac{\boldsymbol{\xi}(\boldsymbol{0})}{\boldsymbol{\xi}(\boldsymbol{r})} \tag{30.4}$$

3.2 If we move our mass, $\boldsymbol{m}$, so it is close to the galaxy centre where $\boldsymbol{\xi}(\boldsymbol{r}) \approx \boldsymbol{\xi}(\boldsymbol{0})$ we have

$$\boldsymbol{F}(\boldsymbol{r}) \;\approx\; -\,\frac{\boldsymbol{G}\,\boldsymbol{M}\,\boldsymbol{m}}{\boldsymbol{r}^{2}}\,\frac{\boldsymbol{\xi}(\boldsymbol{0})}{\boldsymbol{\xi}(\boldsymbol{0})} \;=\; -\,\frac{\boldsymbol{G}\,\boldsymbol{M}\,\boldsymbol{m}}{\boldsymbol{r}^{2}} \tag{30.5}$$

This is simple Newtonian gravitation with nothing added.

3.3 If we move the central mass, $\boldsymbol{M}$, close to the star, where $\boldsymbol{\xi}(\boldsymbol{0}) \approx \boldsymbol{\xi}(\boldsymbol{r})$ we have

$$\boldsymbol{F}(\boldsymbol{r}) \;\approx\; -\,\frac{\boldsymbol{G}\,\boldsymbol{M}\,\boldsymbol{m}}{\boldsymbol{r}^{2}}\,\frac{\boldsymbol{\xi}(\boldsymbol{r})}{\boldsymbol{\xi}(\boldsymbol{r})} \;=\; -\,\frac{\boldsymbol{G}\,\boldsymbol{M}\,\boldsymbol{m}}{\boldsymbol{r}^{2}} \tag{30.6}$$

We again have Newtonian gravitation.

3.4 Finally, if we move the central mass, $\boldsymbol{M}$, and the star, $\boldsymbol{m}$, close together at a completely different location, $\boldsymbol{s}$, we have

$$\boldsymbol{F}(\boldsymbol{r}) \;\approx\; -\,\frac{\boldsymbol{G}\,\boldsymbol{M}\,\boldsymbol{m}}{\boldsymbol{r}^{2}}\,\frac{\boldsymbol{\xi}(\boldsymbol{s})}{\boldsymbol{\xi}(\boldsymbol{s})} \;=\; -\,\frac{\boldsymbol{G}\,\boldsymbol{M}\,\boldsymbol{m}}{\boldsymbol{r}^{2}} \tag{30.7}$$

And we end up, yet again, with Newtonian gravitation.

3.5 Energy scale variations mean we are in the happy situation that, locally and where the two masses are relatively close to one another, the gravitational force is plain Newtonian gravity. This is exactly what we want to be the case.

4 Newtonian limit

4.1 We would really like the gravitational force to return to Newtonian gravity at large distances from the source.

4.2 Our conjecture means that the gravitational force is given by equation 30.1, as set out in paragraph 2.4 above

$$\boldsymbol{F}(\boldsymbol{r}) \;=\; -\frac{\boldsymbol{G\,M\,m}}{\boldsymbol{r^2}}\,\frac{\boldsymbol{\xi(0)}}{\boldsymbol{\xi(r)}} \tag{30.8}$$

4.3 It is clear that we can obtain our goal if at large distances,

$$\boldsymbol{\xi(r)} \;\rightarrow \boldsymbol{1} \tag{30.9}$$

in which case equation 30.8 becomes

$$\boldsymbol{F}(\boldsymbol{r}) \;=\; -\,\frac{\boldsymbol{G}\,\{\boldsymbol{M\,\xi(0)}\}\,\boldsymbol{m}}{\boldsymbol{r^2}} \tag{30.10}$$

4.4 Throughout this work we have assumed the energy scale function ***ξ(r)*** is a simple Gaussian with the form

$$\boldsymbol{\xi(r)} = \;\boldsymbol{1}\;+\;\boldsymbol{\beta}\;\boldsymbol{exp}(-\boldsymbol{r^2}/\boldsymbol{\alpha^2}) \tag{30.11}$$

where $\boldsymbol{\beta}$ is the height of the Gaussian (a pure number); $\boldsymbol{\alpha}$ is the 1/e-width of the Gaussian (a distance).

4.5 At large distances, where $\boldsymbol{r} \gg \boldsymbol{\alpha}$, equation 30.10 becomes

$$\boldsymbol{F}(\boldsymbol{r}) \;=\; -\,\frac{\boldsymbol{G\,M(1+\beta)\,m}}{\boldsymbol{r^2}} \tag{30.12}$$

This has the form we require. It is Newtonian gravitation with the single (fixed) change that the remote mass, ***M***, is modified by a factor ***(1+β)***.

4.6 The factor $\boldsymbol{\beta}$ could be negative (provided $\boldsymbol{1+\beta > 0}$), in which case we have a diminution in the gravitational force. On large (cosmological) scales such regions would become voids as the gravitational attraction trying to hold matter together would be lessened.

5 General Relativity

5.1 Einstein's theory of gravity, general relativity, is a very challenging theory for those physicists and mathematicians who have to work with it. We really don't want to go anywhere near it. And yet we cannot ignore it because we are working with gravity and general relativity is our best theory for it.

5.2 We take a simple view of general relativity and see how far we can go without getting into its difficult bits. In general relativity the gravitational force comes from the curvature of space-time. The curvature of space-time is defined by the metric tensor.

5.3 In the weak field limit (i.e. a long way from the mass) the metric is defined by

$$\boldsymbol{ds^2 = 1(1 + 2\Phi)dt^2 + (1 - 2\Phi)(dx^2 + dy^2 + dz^2)} \qquad (30.13)$$

where the gravitational potential of the remote mass, M, is given by

$$\boldsymbol{\Phi = -\frac{G\,M}{r}} \qquad (30.14)$$

5.4 The gravitational force for this potential is then

$$\boldsymbol{F(r) = -\frac{G\,M\,m}{r^2}} \qquad (30.15)$$

5.5 Comparing equations (30.12) and (30.15) it is clear that our conjecture of energy scale variations satisfies general relativity provided we replace the remote mass ***M*** with ***M(1+β)***, i.e. by having the gravitational potential given by

$$\boldsymbol{\Phi = \frac{G\,M(1+\beta)}{r}} \qquad (30.16)$$

This only holds at large distances, i.e. in the weak field limit.

6 Have we changed Newtonian gravity?

6.1 Our conjecture defines the gravitational force, ***F(r)***, as

$$\boldsymbol{F(r) = -\frac{G\,M\,m}{r^2}\,\frac{\xi(0)}{\xi(r)}} \qquad (30.17)$$

The introduction of the ***ξ(r)*** function for the energy scale variation means we have modified Newton's law of gravity.

6.2 We can define the effective mass $\boldsymbol{M_R}$ as

$$\boldsymbol{M_R} = \boldsymbol{M}\,\frac{\boldsymbol{\xi(0)}}{\boldsymbol{\xi(r)}} \tag{30.18}$$

6.3 Equation (30.17) now becomes

$$\boldsymbol{F(r)} = -\,\frac{\boldsymbol{G\,M_R\,m}}{\boldsymbol{r^2}} \tag{30.19}$$

6.4 Equation 30.19 is good old Newtonian gravity again, where the force is proportional to the product of the masses and inversely proportional to the square of the distance. So we have not changed Newton's law of gravity. What we have changed is the definition of the remote mass $\boldsymbol{M}$.

6.5 So have we or have we not modified Newton's law of gravity? Our conclusion should be that we have changed the energy scale and not the way gravity works.

7 Summary

7.1 The effects on local objects caused by variations in the energy scale of remote objects are determined by local variables. There is no spooky action at a distance.

7.2 Variations in the energy scale disappear at a local level, so normal Newtonian gravity applies to close objects.

7.3 At large distances gravitational effects return to normal Newtonian gravity.

7.4 No changes have to be made to general relativity in situations where the weak field limit applies.

7.5 Our interpretation of energy scale variations is that we have left Newton's law of gravity unchanged.

7.6 Full technical details covering all topics are available as PDF files on web-site:
www.varensca.com

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Way Out

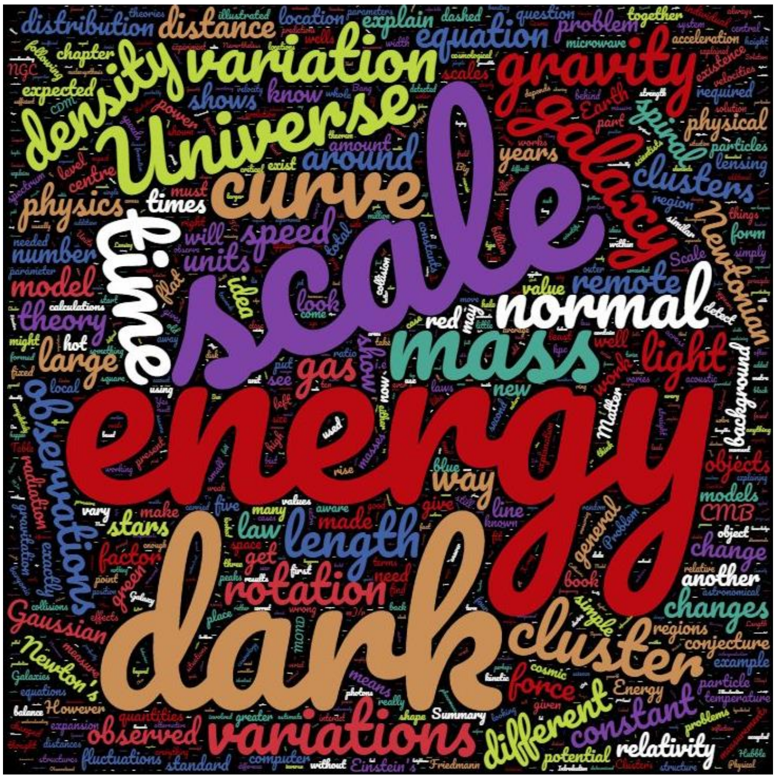

Figure 31.1. Word cloud based on this entire book.

A quick summary of what we've seen, a conclusion, and a good-bye.

1 Summary

1.1 We put forward our new conjecture that the energy scale is not rigid and fixed, but can vary from location to location.

1.2 Our conjecture has no effect on the physical behaviour of objects at a local level. So no experiments on Earth, or in particle accelerators like the LHC, or anywhere in the solar system will detect any deviation from the laws of physics as we know them.

1.3 Our conjecture does have an effect on the physical behaviour of objects in separate locations, through the gravitational interaction. So an energy scale variation can change the effective mass of a galaxy and make the stars in the spiral arms rotate faster than expected. Variations in the energy scale can only be detected through gravity, as far as we are aware. However, we are not changing gravity; we are changing the energy scale.

1.4 The conjecture requires no changes to be made to any of the laws of physics. So no change to Newton's law of gravity, and no change to Einstein's general theory of relativity. We also do not require any changes to any of the physical constants. So both the speed of light and the gravitational constant are absolutely fixed and unchanging.

1.5 Currently we have no theory for energy scale variations: how they are created; how they interact with one another; what shape they have. This makes it difficult to build them into computer models. In particular we cannot replace the ΛCDM model of cosmology with the ESV model (Energy Scale Variation model).

1.6 In this book we've made the assumption that the shape of an energy scale variation is a Gaussian sitting on top of a background energy level. This simple assumption enables us to explain all astronomical observations where the existence of dark matter is invoked. In particular simple Gaussian energy scale variations are extremely successful in reproducing the observed rotation curves of spiral galaxies. For each curve all that is required is the specification of the same two parameters (the height and 1/e-width of the Gaussian).

1.7 For some phenomena the best we can do is illustrate how energy scale variations explain what is going on without the need for dark matter. We can do some simple calculations but they lack the rigour of a proper analysis and detailed computations. So we are in the position where we can show that it is not impossible for energy scale variations to explain the phenomena. We would prefer to be able to give a positive demonstration that energy scale variations do indeed exist as well as do the job.

1.8 A number of predictions have been made for observations that can be carried out. The outcomes to these predictions are different from those made for dark matter and should enable the existence of variations in the energy scale to be substantiated.

1.9 Overall we should be happy that our conjecture of energy scale variations provides a coherent and consistent alternative to dark matter.

1.10 And we remember what we said right at the beginning. We are not sure what is right and what is wrong. Our position is simply that "one way of looking at things is that the energy scale varies from location to location and ..."

2 Some Remarks

2.1 When you think about it our conjecture that the energy scale can vary from location to location is a really simple idea. Surely people would have come up with this idea years and years ago. Apparently not. I can't find any references to the idea that any of the scales of physics might vary. There are many references to variations of the constants of physics, and many references to fine tuning, but nothing on the variation of the scales.

2.2 I also cannot find a simple rebuttal to our conjecture. If it was a completely wrong-headed idea then there would be numerous reasons as to why it is wrong. I can't find a single one. Maybe, as with dark matter, I'm looking in the wrong place.

2.3 A just criticism of this book is that it contains no bibliography and no references. You may ask "how do we know whether anything in this book is true?", or "how do we know that you haven't made the whole thing up?" My response is that I hope you do question everything; that you do go to your local library to consult the science books; that you do search the Internet and check sources such as Wikipedia; that you do think about everything; and that you do make up your own minds.

2.4 There are no acknowledgements. Modern scientific research tends to be carried out by large teams of people working on group enterprises and not by a lone wolf working in isolation. I've been processed by the education system and I am clear in my own mind that the work behind this book would never have happened had I worked in a normal research establishment surrounded by an army of colleagues. So I have no one to acknowledge and I am content with being a lone wolf.

2.5 There are many thousands of scientists working on dark matter. There are a hundreds of scientists working on modifying general relativity. There is one person working on variations of the energy scale.

2.6 All the new ideas put forward in this book are original to me. This includes the conjecture that the energy scale is not fixed and that variations in the energy scale can and do take place. Material up to and including chapter "10: Growth of Structure" is a summary of accumulated knowledge and is clearly not original to me. Material from chapter "11: The Conjecture" onwards is original to me and none of it has been intentionally plagiarised from other people.

2.7 I am in no doubt that some of the points I have made in this book will turn out to be completely wrong or totally misconceived. This will not be surprising as several of the topics covered lie well outside my areas of expertise. Nonetheless the general thrust of the conjecture put forward here should be clear and I am convinced the direction of the overall argument is correct.

2.8 You may have noticed that this book is anonymous, there is no named author. This is deliberate. The argument is often made with scientific work that authorship is essential because authors are responsible for the material they present and they must be accountable for it. Needless to say I don't buy into this argument.

2.9 If the energy scale does vary then a number of questions come to mind; a few of mine are:

- (a) how do we make an energy scale variation?
- (b) is there anything here that might improve people's lives?
- (c) what impact do energy scale variations have on string theory?

and somewhat worryingly

- (d) can we make any money here?
- (e) is there anything here that we can patent?
- (f) can energy scale variations be used to make a weapon?

I'm sure you have questions of your own.

3 What should happen next

3.1 People should, quite rightly, start looking for a rebuttal to our conjecture. Hopefully, like the search for dark matter, they won't find one. We should expect a tide of denials and hostile criticisms. Nevertheless we must encourage as much argument as possible because that's the best way for science to move forward and to make progress.

3.2 Independent researchers should verify our results for the rotation curves of spiral galaxies. To be specific, they should take the latest rotation curve data and attempt to fit it with our two Gaussians solution: one Gaussian for the density distribution and the other Gaussian for the energy scale variation.

3.3 Some astute theoreticians should be able to put our conjecture, stating that the energy scale varies, onto a proper theoretical basis. That should lead to a proper handling of Newton's law of gravity and of Einstein's general theory of relativity.

3.4 Also some smart theoreticians should be able to take our version of the Friedmann as set out in equation (23.1) and put this on a firmer basis. This requires a fresh derivation of the equation for a homogeneous Universe but in the presence of energy scale variations. This is important as much of physical cosmology depends on the Friedmann equation, in particular the ΛCDM model.

3.5 Researchers should undertake new observations to check our predictions, especially the fall off in the rotation curves, and the dispersal of galaxy clusters after collisions.

3.6 Researchers should look for new ways to detect variations in the energy scale, other than through gravitational interactions.

3.7 Our dream for the future might be to uncover a new law of physics covering energy scale variations. We have wonderful laws such as the conservation of energy; something much less grand for energy scale variations would be extremely desirable. And along the same lines we can dream of having an energy scale variation equation.

4 Conclusion

4.1 Well, we are now in the last gallery of the Museum of Dark Matter. We have come a long way and looked at a lot of exhibits, many of which may have been completely new to you. It has been a pleasure for me to show you a few things and I want to thank you for visiting.

4.2 But most of all I want to thank the countless numbers of scientists and engineers who have collected all the items we have seen. In most cases it has taken thousands of people and hundreds of thousands of hours to do the work. It is a painstaking task to build a telescope, to assemble a particle accelerator, or to put a satellite into orbit. It then takes another huge group of people and another huge investment of time to collect the observations, do the science, and publish the results. We are truly fortunate to live in societies where you and I can see all these things for nothing more than a small investment of our own time.

4.3 For my part I have merely come along, picked up the results of others, and applied one simple idea to them. The cost to the public purse (you and me) of our one simple idea is zero. This is somewhat different from the costs of the telescopes, the particle accelerators, the satellites, the research institutions, and the salaries of all the people involved in accumulating the knowledge behind our idea.

4.4 I don't think of myself as a clever person; I'm just mediocre and happy with it. Fortunately for me there's absolutely nothing wrong in being average; in fact the world only works because most people are just that. But you, in reading this book, are clearly smarter than I am. I've come up with "one way of looking at things is ...", but I'm pretty sure you can come up with "a better way of looking at things is ...". So don't delay in getting started on it.

4.5 I apologise for showing that, in all probability, dark matter does not exist. For this I realise only too well that I am a complete spoil sport. I am also aware of the years of effort large numbers of scientists have put into trying to track down dark matter, and that much of this effort may have been for nothing. Dark matter is a concept that has fired the imagination in all sorts of places: TV series; coffee; bicycles; computer security; science fiction stories; and more. With luck the idea of energy scale variations will fire imaginations in different but equally productive ways.

4.6 I apologise there is no gift shop. If dark matter existed then I would be happy for you to go home with a box of it or even a simple postcard. But dark matter does not exist. Instead our museum holds lots of ideas and, at least for now, all these ideas are free. So perhaps we don't really need a gift shop after all.

4.7 I hope you have enjoyed your visit and that you will come back soon. Please remember to leave the door open on your way out. Good-bye.

"One way of looking at things is ..."

32

Quantities and Units

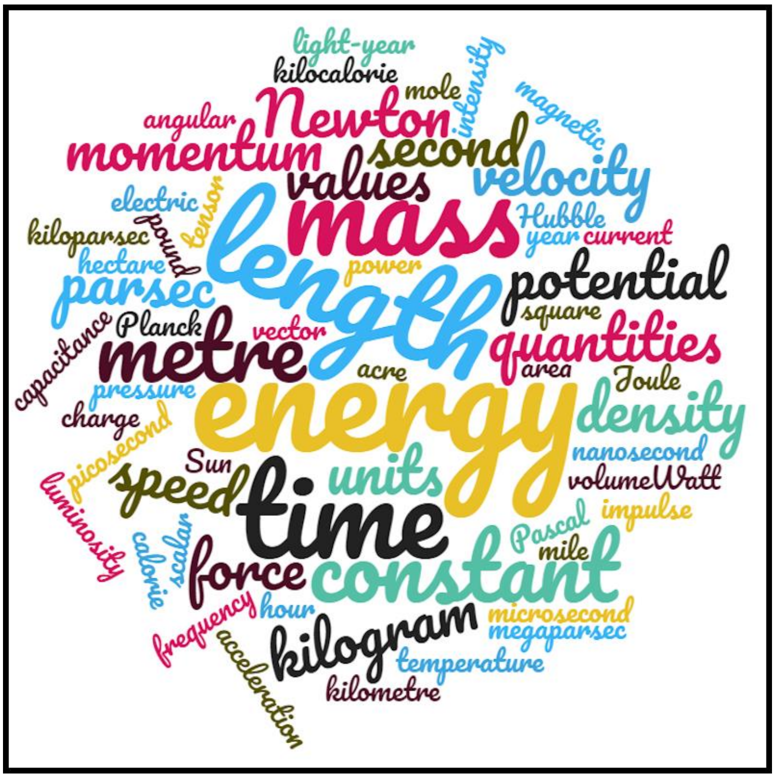

Figure 32.1. Word cloud of some quantities and units.

We list a number of quantities, their values and units, that are relevant to this book.

1.1 Table 32.1: Scales

Quantity	SI Name	SI Unit	M L T	E L T
Length	metre	m	L	L
Time	second	s	T	T
Mass	kilogram	kg	M	E L^{-2} T^{2}
Energy	joule	kg m^{2} s^{-2}	M L^{2} T^{-2}	E

Currently science uses the Mass, Length, Time (MLT) set of scales; shaded in yellow. For our conjecture we prefer to work with Energy, Length, Time (ELT); shaded in green.

1.2 Table 32.2: Common Quantities

Quantity	SI Name	SI Unit	M L T	E L T
Acceleration	-	m s^{-2}	L T^{-2}	L T^{-2}
Angular Momentum	-	kg m^{2} s^{-1}	M L^{2} T^{-1}	E T
Area	square metre	m^{2}	L^{2}	L^{2}
Density	-	kg m^{-3}	M L^{-3}	E L^{-5} T^{2}
Energy	joule	kg m^{2} s^{-2}	M L^{2} T^{-2}	E
Energy Density	joule m^{-3}	kg m^{-1} s^{-2}	M L^{-1} T^{-2}	E L^{-3}
Force	newton	kg m s^{-2}	M L T^{-2}	E L^{-1}
Frequency	hertz	s^{-1}	T^{-1}	T^{-1}
Impulse	newton s	kg m s^{-1}	M L T^{-1}	E L^{-1} T
Length	metre	m	L	L
Mass	kilogram	kg	M	E L^{-2} T^{2}
Momentum	-	kg m s^{-1}	M L T^{-1}	E L^{-1} T
Power	watt	kg m^{-2} s^{-3}	M L^{2} T^{-3}	E T^{-1}
Pressure	pascal	kg m^{-1} s^{-2}	M L^{-1} T^{-2}	E L^{-3}
Speed	-	m s^{-1}	L T^{-1}	L T^{-1}
Time	second	s	T	T
Volume	cubic metre	m^{3}	L^{3}	L^{3}

The SI Name and SI Units are the name and units for quantities as defined by the International System of Units (SI). MLT is mass, length, time. ELT is energy, length time.

1.3 Table 32.3. Fundamental Constants

Constant	Value	Units	M L T	E L T
speed of light, c	2.998×10^{8}	$m\ s^{-1}$	$L\ T^{-1}$	$L\ T^{-1}$
gravitational constant, G	6.674×10^{-11}	$kg^{-1}\ m^{3}\ s^{-2}$	$M^{-1}\ L^{3}\ T^{-2}$	$E^{-1}\ L^{5}\ T^{-4}$
Planck's constant, h	6.626×10^{-34}	joule.s	$M\ L^{2}\ T^{-1}$	E T

1.4 Table 32.4. Physical Constants

Constant	Value	Units
baryon-to-photon ratio	6×10^{-9}	-
critical density, ρ_c	$\sim 10^{-26}$	$kg\ m^{-3}$
Hubble constant, H_0	~70±2	km/s/Mpc
Mass of Sun	1.988×10^{30}	kg

1.5 Table 32.5. Units of Length

Unit	Value
kilometre, km	1.000×10^{3} m
kiloparsec, kpc	3.086×10^{19} m
light year, ly	9.461×10^{15} m
megaparsec, Mpc	3.086×10^{22} m
metre, m	1.000 m
mile, mi	1.609×10^{3} m
parsec, pc	3.086×10^{16} m

All the above length units are expressed in metres, m, and given to 4 significant figures.

1.6 Table 32.6. Units of Time

Unit	Value
billion years	3.156×10^{16} s
hour	3.600×10^{3} s
million years	3.156×10^{13} s
second, s	1.000 s
year, yr	3.156×10^{7} s

All the above time units are expressed in seconds, s, and given to 4 significant figures.

1.7 Table 32.7. Units of Mass

Unit	Value
Earth mass	5.972×10^{24} kg
kilogram, kg	1.000 kg
pound (UK)	4.536×10^{-1} kg
solar mass	1.988×10^{30} kg
ton (UK)	1.016×10^{3} kg

All the above mass units are expressed in kilograms, kg, and given to 4 significant figures.

1.8 Table 32.8. Units of Energy

Unit	Value
erg	1.000×10^{-7} J
joule	1.000 J
kilocalorie, kcal	4.184×10^{3} J
kiloton (of TNT)	4.184×10^{12} J

All the above energy units are expressed in joules, J, and given to 4 significant figures.

1.9 Table 32.9. Planck Units

Unit	Formula	Value
Planck energy	$\sqrt{\hbar\, \boldsymbol{c}^5/\boldsymbol{G}}$	1.956 × 10^{9} J
Planck length	$\sqrt{\boldsymbol{G}\, \hbar/\boldsymbol{c}^3}$	1.616 × 10^{-35} m
Planck mass	$\sqrt{\hbar\, \boldsymbol{c}/\boldsymbol{G}}$	2.176 × 10^{-8} kg
Planck time	$\sqrt{\boldsymbol{G}\, \hbar/\boldsymbol{c}^5}$	5.391 × 10^{-44} s

where $\hbar = h/2\pi$ is the reduced Planck constant.

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Abbreviations and Glossary

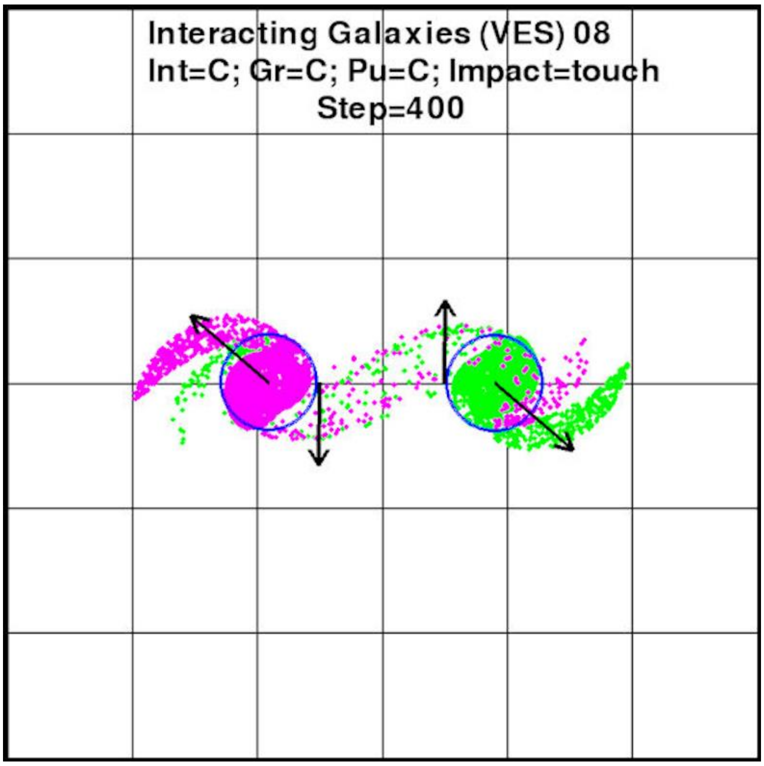

Figure 33.1: A frame from a simple simulation of two interacting disk galaxies shortly after their closest approach. Computations assume both galaxies are embedded in an energy scale variation. The production of leading tidal tails is very clear. The short arrows show the direction of rotation. The long arrows from the galaxy centres show the direction of motion.

Λ	Lambda, Greek letter used for the cosmological constant; usually associated with dark energy.
ΛCDM	Lambda-CDM is the widely accepted model for explaining the Universe. It involves Λ (Lambda) the cosmological constant and cold dark matter (CDM).

acoustic oscillation	fancy name for a sound wave.

BAO	baryon acoustic oscillation
baryon	sub-atomic particle made of 3 quarks; e.g. proton, neutron.
baryon acoustic oscillation	sound waves in matter in the early Universe up to the time of the cosmic microwave background
baryonic matter	term used by astronomers for matter made of particles in the standard model.
Big Bang	origin of the Universe when space and time were created, together with all the matter and energy.

CDM	cold dark matter
cluster of galaxies	collection of galaxies that are gravitationally bound together, contain from a few hundred to several thousand galaxies.
CMB	Cosmic Microwave Background
conjecture	an idea that is incomplete, usually for mathematical ideas that cannot be proved.
Cosmic Microwave Background	Light from the early Universe (~380,000 years after Big Bang) when neutral atoms were first formed. Currently observed in the microwave part of the spectrum. It has the shape of a black body at a temperature of 2.73 K, and shows fluctuations at the level of 1 part in 100,000.
cosmological constant	constant term that can be added to Einstein's field equations for general relativity. It is currently thought to be synonymous with dark energy. It is denoted by Λ.
cosmology	physical cosmology is the scientific study of the Universe.

dark energy	hypothetical energy introduced to account for the accelerating expansion of the Universe. Currently dark energy accounts for 70% of the energy density in the Universe.
dark matter	hypothetical non-baryonic matter introduced to account for a large number of astronomical phenomena where there appears to be a large deficit of gravitating mass. Currently dark matter accounts for 25% of the energy density in the Universe.

Einstein, Albert	(1879-1955) German physicist
Eureka!	exclamation attributed to Greek physicist Archimedes upon discovering his rule on buoyancy.
Feynman, Richard.	(1918-1988) US physicist.
fluctuations	small variations in density or temperature in the early Universe.

Friedmann, Alexander	(1888-1925) Russian mathematician.
Friedmann equation	Equation, derived by Friedmann from Einstein's general relativity, that defines how a homogeneous Universe must evolve.

Gauss, Karl Friedrich	(1777-1855) German mathematician
Gaussian	the normal distribution, often referred to as the "bell curve".
general relativity	Einstein's theory that extends special relativity to cover gravity, which arises through the geometric curvature of space-time.
gravitational lensing	the bending of light from a remote source by a nearer source along the light path. Often a remote galaxy being lensed by an intervening cluster of galaxies.
gravitational potential energy	the energy an object has arising from its position in the gravitational field produced by other objects.

Hubble, Edwin	(1889-1953) US astronomer.
Hubble constant	The current value of the Hubble parameter, H_0, ~70 km/s/Mpc.
Hubble's law	linear relationship linking the red-shift of a remote object to its distance.
Hubble parameter	The "constant" in the Hubble law; it changes with time.
hydrostatic equilibrium	the state of balance in a gas or fluid between gravitational attraction and pressure. Stars are in such a state.
hypothesis	an idea for explaining some phenomenon, often in physics for an incomplete theory

inflation	the theory that the Universe underwent a period of exponential expansion immediately after the Big Bang.

kg	kilogram: standard of mass.
kinetic energy	the energy an object has arising from its motion
kpc	kiloparsec

Lambda-CDM	Lambda cold dark matter. The widely accepted model for the evolution of the Universe.
LHC	Large Hadron Collider; a particle accelerator at CERN, Geneva.

m	metre: standard unit of length.
mass-to-light ratio	the ratio of the mass of an object to the amount of light it emits. Normalised so that the Sun has a value of 1.0. Spiral galaxies have values around 5.
Mencken, HL.	(1880-1956) US writer.
Milgrom, Mordehai.	(1946-) Israeli physicist.
MOND	MOdified Newtonian Dynamics, a modification of Newtonian gravity put forward by Mordehai Milgrom for explaining the rotation curves of spiral galaxies.

Mpc	megaparsec: unit of distance. 1 Mpc = 3.26 million light years. 1 Mpc = 3.086 x 10^{22} m.
museum	a building where items of interest are stored and displayed.

neutrino	light neutral elementary particle, three flavours: electron, muon, tau.
neutron	neutral elementary particle, slightly more massive than the proton, made of three quarks
Newton, Sir Isaac Newton	(1643-1727) British scientist.
Newton's laws of motion:	(1) a body remains at rest or uniform motion unless acted upon by a force; (2) force = mass x acceleration; (3) action and reaction are equal and opposite.
Newton's law of gravitation:	gravitational force of attraction between two bodies is proportional to the product of the masses and inversely proportional to the square of the distance between them.
NGC	New General Catalogue: catalogue of clusters; nebulae; galaxies.
non-baryonic matter	term used by astronomers for matter made of particles that are not in the standard model; often used to describe dark matter.

pc	parsec: unit of distance. 1 pc = 3.26 light years. 1 pc = 3.086 x 10^{16} m.
potential energy	the energy an object has arising from its position relative to other objects, or from other factors. See "gravitational potential energy".
power spectrum	the splitting of a spectrum into the power that is carried by different frequencies. It is the Fourier transform of the spectrum.
proton	elementary particle, with a positive charge, made of three quarks

quantum mechanics	theory that describes the behaviour of particles in the standard model
quark	fundamental particle, six flavours: up, down, strange, charm, bottom, top.

relativity	the idea that there is no absolute space or time, and that everything is relative. See "special relativity", "general relativity".
rotation curve:	graph of the orbital (rotation) speed against distance, usually for spiral galaxies.
Rubin, Vera	(1928-2016) US astronomer.
Rumsfeld, Donald	(1932-) US politician

s	second: standard of time.
special relativity	Einstein's theory that space and time form a single four-dimensional space-time where events and motions are all relative to the observer.
Standard Model	Theory that covers all the elementary particles and the three forces of electromagnetism, strong nuclear force, weak nuclear force.

strong lensing	gravitational lensing of a remote galaxy by a cluster of galaxies giving rise to arcs of light or an Einstein ring or Einstein cross. Can be used to map the distribution of gravitating mass in the intervening object.
structure	term used by astronomers for objects formed by gravity; typically applied to cosmic filaments, galaxies, galaxy clusters, voids, etc.
Universe	the entirety of everything we can observe; the whole of space and time; stars, galaxies, and everything else.
varensca	variation of the energy scale
virial theorem	theorem of mechanics where for stable (relaxed) systems the total kinetic energy is double the total potential energy.
void	large region of space where few galaxies are found
weak lensing	distortion of shapes of remote galaxies by intervening clusters of galaxies. Can be used to map the distribution of gravitating mass in the intervening object.
WIMP	Weakly-Interacting Massive Particle; a hypothetical particle that interacts with matter through the weak nuclear force.
Zwicky, Fritz	(1898-1974) Swiss astronomer

"One way of looking at things is ..."