How dark is the Universe?

An evaluation of two competing astrophysical theories

Figure from Astronomy Picture of the Day (Copyright: Robert Gendler)

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Abstract

Is there a better theory among two rivalling scientific theories? Hypothetico-deductive (HD) testing, originally designed by Hempel and Popper, has been explicated by Kuipers (2000) in its straightforward comparative form to answer exactly these sorts of questions. This master thesis provides a (first?) practical and contemporary example of such a comparison, from the field of astronomy.

Both rivalling theories considered here attempt to explain the same discrepancies in observations: the unexpected high speeds of objects in the outer parts of galaxies, or galaxy systems. It seems that there is not enough mass inside these systems to keep these objects in their orbits. The (Cold) Dark Matter (CDM) solution to this problem, supported by most astronomers, assumes there is more matter inside a galaxy than we can see or measure: part of it is dark. Modified Newtonian Dynamics (MOND), on the other hand, argues that not the postulated matter content of the Universe, but our laws of gravity should be changed.

Is the majority of the astronomical community right in regarding CDM as the better theory? I show in this thesis that from a purely empirical point of view the theories are in a state of divided success. However, from aesthetic arguments, as classified by McAllister (1996), CDM theory seems more appealing, which might explain its higher popularity. Furthermore, I discuss a future outlook and whether it will be possible to combine these two very different, but (partly) successful, theories into one.

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Chapter 1

Introduction & Outline

For my masters thesis in philosophy I was looking for a topic that would combine my two main fields of interest: astronomy and philosophy. Apart from being a philosophy (of science) student I am an astronomer as well and I thus get to deal with scientific practice every day. As every scientist should, I like to change viewpoints every now and then, take somewhat more distance from my daily research and look toward science in a more philosophical way.

Through the lively discussions often held during lunch talks at the Kapteyn Astronomical Institute in Groningen, I got in touch with Modified Newtonian Dynamics (MOND) theory. As I soon learned, this theory proposes an alternative for (Cold) Dark Matter (CDM) theory, which I was very familiar with through classes in cosmology and galaxy formation. However, MOND and CDM theory show some very fundamental differences. (Cold) dark matter theory solves some observational astronomical problems (discussed in much more detail in this thesis) by proposing a form of matter that can not be seen, but acts on gravity. MOND takes a very different approach and proposes to alter not the matter content of the Universe, but the gravitational laws that describe it.

This fundamental difference of approach already raised my interest for the topic. On top of this, the question came to mind why I had been taught so much about (cold) dark matter theory, and even used it in research, without learning much about the (viable?) alternative theory MOND? Although MOND has shown some phenomenological successes in the past decades, there are still very few scientists supporting it. A key question raised in this thesis is whether there is a justification for this. Is the majority of the scientific community right in following CDM theory and discarding MOND? Is CDM theory truly a better theory?

Outline of this thesis

To answer these questions this thesis provides a qualitative evaluation of the two competing theories. Such a thorough approach that compares both the empirical and non-empirical qualities of two theories is not something encountered often in the scientific world. However, we think such an approach should be pursued much more often as it gives a more objective approach on the abilities and flaws of scientific theories people work with every day.

I will first start by explaining the observations that led to the foundation of both theories. Subsequently I will give an introduction in both theories and the kind of Universes they predict if they are true. In Chapter 3 I will then give an introduction into philosophy of science in general and hypothetico-deductive testing, the approach taken in this thesis to compare both theories to each other, in particular. Also, some attention will be given to non-empirical arguments that can play a great role in scientific practice. Chapters 4 and 5 are devoted to the empirical successes and problems of consecutively MOND and dark matter theory. Both chapters are concluded with an evaluation report which briefly lists the problems and successes discussed. The subsequent chapter tries to put both theories together in an empirical comparative evaluation. In Chapter 7 the non-empirical arguments in favour of and against both theories are investigated. Finally, in the Discussion and Conclusions the main question of this thesis will be discussed and eventually answered: "Is there a better theory?

Chapter 2

One problem, two solutions..

2.1 Zwicky's discovery

Generally scientists believe that all kinds of systems on different scales are held together through the same laws of gravity. For example, it is gravity which makes the Earth and all the other planets revolve around the Sun. But gravity also makes this solar system which we live revolve around the centre of our galaxy, a massive gravitational bound assembly of millions of stars called "the Milky Way". Our galaxy is certainly not the only galaxy in the Universe, we see galaxies in various forms and masses everywhere. Under gravitational force again, these galaxies group together as well, forming what we call clusters. In the 1930's astronomer Fritz Zwicky discovered something very peculiar about the movement of individual galaxies grouped together in a cluster. In a cluster the speeds of the individual galaxies have to be in an equilibrium state: large enough to prevent the gravitational force between them to pull all galaxies to one point, but small enough to keep them from flying out of the cluster. By studying the movements of the individual galaxies in the cluster, you can thus infer the required gravitational pull to keep the galaxies in such a system, and therefore the mass of the cluster. Doing so for the so-called Coma cluster, Zwicky noticed that the speeds of the individual galaxies were so high that, in order to keep the system from flying apart, the cluster mass had to be ten times larger than all the visible mass in the cluster together! Though his results were doubted at first, scientists would later repeat his work, also for other clusters and even for superclusters (clusters of clusters of galaxies) and prove Zwicky right. About ninety percent of the mass that the galaxies "feel" cannot be seen by us in any way. Zwicky's discovery would prove to be critical to our understanding of the Universe.

Zwicky's discovery would also be confirmed and strengthened by the study of the movements of material within a single galaxy. Galaxies themselves consist of various different components. Next to stars, which are easy to see because they shine brightly, galaxies also host a lot of gas and dust. Though this material generally emits hardly any light in the wavelengths we can see, it is possible to detect it in other wavelengths. For instance, the presence of gas clouds can be detected by looking at the 21 centimetre wavelength in the light spectrum. This wavelength is typical for neutral hydrogen, the major component of these clouds. Furthermore, when observing a gas cloud in a galaxy by determining the 21 cm line, the speed of the cloud can be measured as well using the Doppler shift. Also subject to the gravitational pull of the galaxy system and the same laws of gravity, the cloud will orbit the galaxy centre the same way as stars do (or galaxies orbiting the centre of mass in a cluster). The orbital speeds of the material in the galaxy can be mapped to large distances out of the galactic centre, because these massive gas clouds reside in the outer parts of the galaxy.

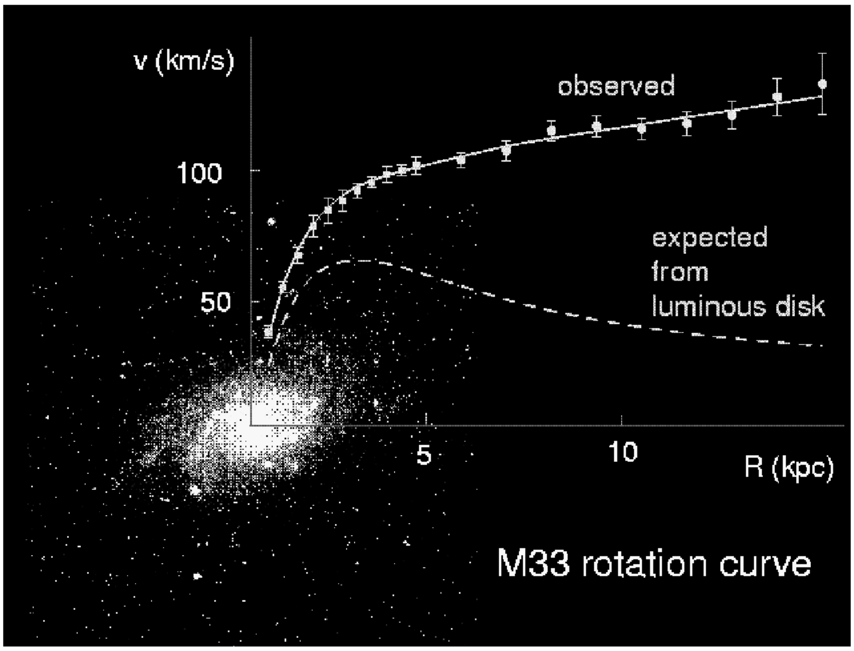

Figure 2.1: An optical image of the galaxy nearest to us, Andromeda, with superimposed the observed velocities of the stars and clouds with radius (dots with error bars) and the expected velocities from the distribution of luminous matter (dashed line). (From ref. [KM02], original rotation curves from [Roy00].)

The measurements of the speeds of various clouds confirmed Zwicky's earlier discovery in galaxy clusters: in the outskirts of galaxies the material possesses such high speeds that, in order to be bound to the galaxy the gravitational pull has to be much stronger than the gravitational pull from the observable (luminous) mass in the galaxy. This effect is seen more dominantly farther away from the galactic centre. Some clouds in the extreme outskirts of galaxies were observed to move at the same pace as clouds five times closer to the centre, whereas the laws of gravity would predict them to move more slowly (if no extra gravitational pull is involved). In Figure 2.1 the difference between the expected and observed velocities of clouds in our neighbouring galaxy, Andromeda, are shown.

There are only two ways to explain the high speeds of these clouds and, similarly, the rapid movements of galaxies in galaxy clusters. We have to conclude either that Newton's law of gravitation breaks down in these circumstances, or that there is an extra gravitational attraction from invisible matter [Liv00]. Indeed both of these solutions are explored by scientists. These two solutions to the same observational problem will lead to very different views on how our Universe is built and behaves as will be discussed in more detail in this thesis.

2.2 The Concordance model: (Cold) dark matter theory

Most scientists today believe that the surprisingly high velocities in galaxies and clusters are caused by matter that can not be seen by us, but is nonetheless felt by the luminous matter through gravitational force. In galaxies this mysterious mass component resides in halos that can be much larger than the galaxy itself. Sometimes these dark halos can even touch each other whereas the galaxies themselves are not. A possible scale is illustrated in Figure 2.2. This unseen matter will have mass and does obey the laws of gravity, but it will not or hardly interact with itself or other mass or radiation and therefore emit no radiation itself. Because of this property this mysterious matter is usually referred to as "dark". There are several possibilities of what this dark matter could be. I will first shortly give the most important dark matter candidates, before discussing them in more detail.

Dark matter candidates:

- Ordinary, but non-luminous matter:
  - small stars (called 'brown dwarfs')
  - black holes (very, very compact objects)
- Neutrinos
- Exotic non-baryonic particles

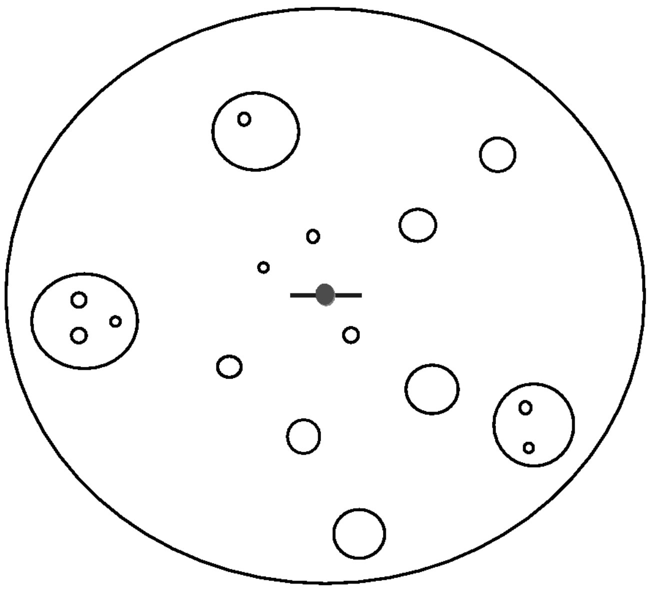

Figure 2.2: A dark matter view of a galaxy. The small dot and line in the middle represent the visible part of the galaxy. The large circle is the dark matter halo around it which is much larger than the galaxy itself. Even this dark halo has some substructures, which are denser places, here indicated as smaller circles. (Credit: Ben Moore, image taken from his lecture notes at the Milky Way summer school in Heidelberg 2007)

2.2.1 Ordinary non-luminous matter

There are several objects in the Universe which are hard to detect and were considered to be a serious candidate for the mysterious dark matter around galaxies and clusters. The two most probable forms for ordinary matter (built up from protons and neutrons, like all the matter we see around us) to become invisible for our telescopes at all wavelengths is either when it is hidden in stars which are not massive enough to start fusion processes and will thus never shine (these objects are called brown dwarfs), or the end product of the lives of very massive stars, which become black holes. These kind of objects are called MACHOs, for MAssive Compact Halo Objects. The MACHO solution does have problems, however. If we expect a large fraction of the dark matter mass to be in the form of brown dwarfs, this means huge amounts of these objects must reside in the halos of galaxies. Brown dwarfs themselves are hard to detect, although they do emit a small amount of infrared radiation, and black holes can not be detected at all. These endpoints of massive stars are so dense that their gravitational field is so strong it even bends light beams so heavily that they will not be able to leave the black hole. But because these objects are heavy and certainly much denser than their environment, it is expected that they will distort the star light from stars behind it in a particular way. Several monitoring experiments have been carried out in the past decades to detect such distortions of distant star light by the outskirts of the Milky Way in which the MACHOs are thought to reside, but so far with no success. Subsequent monitoring of such effects in the direction of shining stars showed that the method itself is working properly and that it is therefore very probable that these objects simply do not exist in such large quantities.

Another problem with black holes is that they are formed in very violent processes. Although the black hole itself will be invisible the surroundings of it should be distorted and enriched with heavier atoms. We do not observe the quantity of heavier atoms in galaxies today that would have been produced in the formation of black holes in the large quantities needed to produce enough dark matter. The only possibility for black hole mass to contribute substantially to the dark matter mass, is when massive black holes can be formed in a way in which they will leave less material behind. Theorists think this might happen if really massive stars (over a hundred times more massive than the Sun) die, but these stars are highly theoretical as they have never been observed. Also, there are more fundamental and theoretical reasons to believe that the dark matter mass will not be constituted from ordinary matter, as will be discussed in the last section of this chapter.

2.2.2 Neutrinos

A second dark matter candidate is the *neutrino*. This particle is built into the Standard Model of particle physics and its existence is verified by experiments. In the Standard Model it is expected that in the big bang hundreds of millions of neutrinos were produced for every proton (which is the building block of almost all matter we see around us). Also neutrinos are produced in processes which involve the breaking up of atoms, as happens for instance when cosmic rays from the Sun hit the Earth's atmosphere. Neutrinos have no electric charge and they do not emit any radiation. They also interact only very weakly with matter. In fact, every single second, hundreds of billions of neutrinos fly through our body and the Earth, while on average only once every seventy years one of those neutrinos will interact with an atom in your body [Liv00].

Neutrinos were first thought to have no mass at all, but experiments with giant neutrino detectors showed that they do have a very small mass between of one-tenthousandth of 1 percent and four thousandth of 1 percent of the mass of an electron. This may sound very small, but neutrinos are thought to be very numerous and their total contribution to the mass in the Universe could be important. The experiments could unfortunately just provide a lower and upper limit on the mass. However, there are other hints that even if neutrinos have a mass, they can not be the major form of dark matter. This has to do with the way galaxies are thought to form. Scientists believe the structure in the Universe is formed hierarchically, which basically means bottom-up; starting with smaller structures which eventually grow together to form larger structures. Generally this process is tested with computer simulations and such a structure-forming algorithm seems to match relatively well with the structure we see around us in the Universe today. With neutrinos being the dominant dark matter material such a bottom-up approach is not possible, neutrinos are light and have large random velocities. They are therefore categorised as *hot dark matter*. Early formed small structures will be destroyed and fly apart quickly if they were made out of any kind of hot matter, because of the high velocities of the individual particles. In a neutrino dominated picture it would therefore be very hard to construct massive systems like the galaxies that we see around us today. Also it is unlikely that this hot matter will reside quietly in the outskirts of galaxies, which is where we find the dark matter to be.

2.2.3 Exotic non-baryonic particles

In order to reconcile dark matter particles with our formation picture of structures in the Universe, it needs to be *cold*. Because of this constraint the most dominant dark matter theory and practically all possible modifications of it use cold dark matter. This is the reason why the theory in this thesis is abbreviated to **C**DM theory. 'Cold' in this respect means that the particles must either be relatively heavy, or have slow random motions. Particles of the first kind (at least 50 to 500 times heavier than a proton) are called WIMPs (Weakly Interacting Massive Particles). These WIMPs are generally thought to be non-baryonic, which means they are, unlike everything we know and see around us, not built up out of protons and neutrons. For particle theorists it did not come as a surprise that cosmology needed a kind of particles that is yet undiscovered. Theories of supersymmetry (abbreviated as SUSY) that were developed in the 1970s already predicted whole families of unknown particles, all of which are uncharged so they interact with other matter only very weakly. Most of these particles would have been created in the early universe, but would be unstable and fall apart in no time, but the leading WIMP candidates are stable. These particles are known as *neutralinos*. No neutralinos are detected today, but there are huge experiments built to do so (such as the Large Hadron Collider at CERN, Geneva). The general expectation is that if the supersymmetry theories are right in their predictions, some neutralinos will be detected within two decades.

As described above, cold dark matter particles could also be of low mass, if they would be created in a cold state and thus have low velocity. An example of such an exotic particle, is the *axion*, also predicted by particle physicists. This particle is extremely light and can be transformed in radiation in a strong magnetic field. In search for the axion also experiments have designed which are determined to find it, but no successes have been reported to date.

2.2.4 Flatness of the Universe and why dark matter is probably non-baryonic

Research in the field of cosmology, the study of the Universe as a whole, also raises questions like: “What will the final fate of the Universe be?”. When assuming that the Universe did start in a big bang and has been expanding ever since, a theory almost all astronomers are convinced of, there are three possibilities for the future of the whole Universe. You can compare this scenario with throwing a ball in the air (example taken from [Liv00]). Although you give the ball a certain initial energy and speed, here at the surface of the Earth the gravitational pull on the ball will win over the kinetic energy you gave it and will draw the ball back down into your hand. However, if you put the ball inside a rocket of which the rocket engines will give it much more thrust than you could ever throw it, it might get enough energy to totally escape from the Earth’s gravitational field. A rather similar process is happening in the Universe as a whole. In the big bang the Universe got an initial expansion and it is expanding still. But will it expand forever? That depends on how much mass the Universe has inside. If there is enough mass the mutual gravitational attraction within the Universe will eventually stop the expansion and pull everything back together into one point again, just as the ball falls back in your hand when you throw it vertically up into the air. This fate is called the *big crunch*. However when there is not enough mass to stop the expansion and turn it around, the Universe will be expanding forever and the Universe will cool down and approach a cold death. There is a third, and very interesting possibility, however. If the mass within the Universe reaches one particular level, called the critical mass, the gravitational pull will not be sufficient to turn it around, but it will slow the initial expansion down until it’s velocity is zero in infinite time. It is as if the ball we throw in the air is slowing down and slowing down, but never turns around and just continues to slow down forever. This third possibility is an unstable equilibrium, a little more or a little less mass will push the solution to forever expanding or a crunching Universe. The reason why this possibility is regarded as being interesting is because empirical mass counts in the Universe (using for instance movements of clusters and gravitational lensing as discussed before), come to the conclusion that the total mass in the Universe is 0.1 ± 0.15 times the critical density [Kra07]. This may seem far from the critical density value, but because the critical density situation is an unstable equilibrium, it would have evolved a lot over time since the beginning of the Universe. An initial density of 1 times the critical density in the early Universe would still be 1, but if the mass density now really is 0.1 this would mean the initial density of the Universe had to be 0.999999999999999 (only different by 1 part over 10^{15} [Liv00]). Many scientists believe that this value is too close to 1 to be coincidental, they think we are simply missing still an amount of the mass, which is for instance hiding between superclusters and that the density today is precisely the critical density, 1. Subsequently, the inflationary model, a theoretical model which describes the Universe in the first 10^{-32} seconds and predict it to develop very small fluctuations in density from which all structure might grow further on, also predicts the density to be exactly the critical density.

Measurements of the mass density in the Universe also directly influence the dark matter problem through the measurements of deuterium. The chemical element deuterium was formed in the first three minutes after the big bang and is decreasing ever since, because it is destroyed in stars. It is important to measure the deuterium fraction in the early universe, because the fraction of deuterium is a probe for the initial density of all baryons in the Universe. If the density of baryons is too high, the deuterium in the early universe would have all been destroyed by now. If the density of baryons were too low, deuterium would as a consequence be overproduced. Measurements of the deuterium fraction thus place limits on the density of all the baryons in the Universe. From measurements of the deuterium fraction in several systems the estimated baryon fraction in the Universe is 0.02 +/- 0.002 of the critical density [Kra07] and certainly not exceeding 0.1 times the critical density [Liv00]. As we have seen above, several measurements of the density of the Universe are already exceeding this value, quite aside from the fact that many scientists believe the eventual density will be 1. The large discrepancies between the upper limit the density of baryons can have from deuterium measurements and the total measured density shows the remaining dark component has to be non-baryonic.

2.2.5 The Concordance Model and the Cosmological Constant

In the “Concordance Model”, which describes the Universe as the majority of the astronomers believe it to be, about 90% of the matter content of the Universe consists of a non-baryonic cold dark matter component. Only about 10% is made up of ordinary matter, built up from protons and neutrons, as we see it around us. These values are in agreement with the measurements of the baryonic content in the Universe. However, if we are not looking at the matter in the Universe, but at the total energy density (which is convertible to a sort of gravity due to Einstein's $E = mc^2$), then we find another component which we haven't discussed yet. Only 23% of energy density in the Universe is due to dark matter and just a minor 4% is due to ordinary matter. The remaining 73% of energy is produced by the so-called *dark energy* or *cosmological constant*.

The cosmological constant was first added to the equations of general relativity by Einstein to keep the Universe steady. However, when the big bang model became generally accepted he realised the constant was no longer necessary and he called it "his greatest blunder". Although Einstein left his faith in the constant, including the constant remained a valuable solution to the equations of general relativity. Today, the constant is used to describe the energy of the empty space or vacuum. From quantum mechanics we know that even vacuum space can have a certain energy, which could be described as a negative pressure. There are several ways to measure the value for the cosmological constant and attempts have been made from measurements of the first radiation we can see after the big bang and from theoretical models describing the behaviour of the vacuum the first 10^{-30} seconds after the big bang. In both approaches the cosmological constant is believed to have a value of 0.6 to 0.7 of the critical energy density.

2.3 Modified Newtonian Dynamics (MOND)

The second theory discussed in this thesis: Modified Newtonian Dynamics, is to date the most successful theory that explains the discrepancies between rotational velocities in galaxies and galaxy clusters by modifying the laws of gravity, using no invisible matter component. Only a minority of the astronomical society currently thinks MOND is the most adequate solution for the problems described in the first section of this chapter. A majority of scientists believes that the laws of gravity should be maintained and that it is better to adopt an unseen form of matter to explain the observed discrepancies as was discussed in more detail in the previous section.

MOND theory assumes that gravity in the outskirts of galaxies and galaxy clusters can not be described by the laws of gravity of Newton, which were later generalised by Einstein. The basic concept behind the idea of MOND, first put forward in a series of papers in 1983 by Mordehai Milgrom, is that in weak gravitational fields like they exist in outskirts of a galaxy or galaxy cluster, the gravitational force does not weaken with distance as quickly as described by Newton's law. Instead of weakening with the distance squared, it would weaken proportional to distance. This would solve the problem of the rotation curves of galaxies being flat in the outskirts, because this is exactly the behaviour you would expect if the gravitational force weakens with distance, without any need to put in a mysterious dark matter component. The theory is most often described as a modification of the gravitational acceleration[1]. In classical physics the Newtonian gravitational acceleration at a distance R

[1] MONDian physics has also occasionally been described as a modification of *inertia*, changing Newton's second law: $F = ma$. In the MONDian regime this would then change to: $F = ma^2/a_0$. This approach is more drastic since it changes the behaviour of all accelerations, not only those under gravitational force. In this thesis we will consider MOND as a modification of gravity and not of inertia, because it is the most widely used approach.

from a point mass M and given the Universal gravitational constant, G, is given by:

$$\vec{g}_N = \frac{GM}{R^2} \tag{2.1}$$

The MONDian description of gravitational acceleration relates to the Newtonian description in the following way:

$$\vec{g} \cdot \mu(\vec{g}/a_0) = \vec{g}_N \tag{2.2}$$

In the MONDian description we further find μ which is a function of $\vec{g}$ and a constant called a_0. For the function μ the following rules apply:

- $\mu = \vec{g}/a_0 \quad \text{if} \quad \vec{g} << a_0$
- $\mu = 1 \quad \text{if} \quad \vec{g} >> a_0$

Basically this means that there is a critical limit of acceleration (a_0) at which the gravitational acceleration felt by any particle changes from a Newtonian description to a MONDian description. If $\vec{g} >> a_0$ then $\mu = 1$ and $\vec{g} = \vec{g}_N$. In this regime, at acceleration higher than a_0 nothing special happens and all the gravitational effects can be described with the familiar Newtonian formula given above. However, when $\vec{g} << a_0$ then $\mu = \vec{g}/a_0$ and then:

$$\vec{g} \cdot \frac{\vec{g}}{a_0} = \vec{g}_N \quad \rightarrow \quad \vec{g} = \sqrt{\vec{g}_N a_0} \tag{2.3}$$

In between these two values, so if $\vec{g}$ and a_0 are comparable, μ is in a transition phase between 1 and a/a_0. The shape of this transition depends on the exact form of μ. The shape of this transition function has not been determined precisely although from observations MOND scientists think it should be rather sharp, i.e. go from a Newtonian regime to a MOND regime relatively quickly.

In summary: in the low acceleration field, the gravitational acceleration felt by a particle changes compared to the Newtonian description that scientists use and have used for ages to calculate the mass needed to keep a galaxy or cluster together.

If we make the same calculation here, balancing the acceleration of the rotational velocities of stars or clouds (V_c) in a galaxy with the gravitational acceleration exerted by the mass inside the galaxy, we see that in the MONDian regime this explains the flat rotation curves in the outskirts of galaxies and galaxy clusters. In these regimes where the rotation curves are flat the gravitational field is low and we thus use the MONDian formulas. We have seen that in this regime:

$$\vec{g} = \sqrt{\vec{g}_N a_0} \quad \rightarrow \quad \vec{g} = \sqrt{\frac{GM}{R^2} a_0} \tag{2.4}$$

The centripetal acceleration from the rotating stars and clouds that balances this gravitational acceleration can be described by:

$$\vec{a}_c = \frac{V_c^2}{R} \tag{2.5}$$

In equilibrium we thus find:

$$\vec{a}_c = \vec{g} \quad \rightarrow \quad \frac{V_c^2}{R} = \sqrt{\frac{GM}{R^2} a_0} \quad \rightarrow \quad V_c^2 = \sqrt{GMa_0} \tag{2.6}$$

There is no R any more in this last equation, which means that the rotational velocity (V_c) has become independent of the radius to the centre of the Galaxy, it has become constant. This is exactly the kind of behaviour MOND was set up to explain.

Observable effects

In the everyday world around us and even in most of the solar system $\vec{g}$ is much larger than a_0, so the effect of the changed Newtonian law would not be observable. The weak gravitational force fields in which the effect could typically be observed are the outskirts of galaxies or the space between galaxy clusters. But there might also be some places in the solar system (far away from the outer planets for instance) $\vec{g}$ could be weaker than a_0. Inside these low gravitational regimes the MOND laws take over from the Newtonian laws and as a result of this for instance stars and clouds in the outer regime of galaxies will approximately have the same orbital velocities as objects which are much closer to the centre of the galaxy or cluster. We have already seen that this explains the flat end of the curve, as it was for example shown in Figure 2.1. Apart from the high orbital speeds observed in the outer skirts of galaxies, MOND laws also describe and predict several other observational quantities about galaxies and predictions can be made of what the Universe should look like if this theory would be correct. The precise (observational) successes, problems and predictions of MOND theory are described in much detail in Chapter 4.

From ad hoc hypothesis to theory

For years, the biggest problem MOND as a theory had to face, was its ad hoc hypothesis character. While Newton's laws of gravity can be seen as a low limit case of Einstein's general relativity laws, there was no theory underlying MOND laws. No physical process was known which would cause the laws of gravity to make such a sudden change if the gravitational field became weaker. A second, maybe even stronger objection to the theory was that, though mostly focusing on the Newtonian laws, MOND would also affect the well tested and widely accepted general relativity theory by Einstein. MOND scientists had to find a way to reconcile their theory with Einstein's theory in a relativistic limit. This problem was finally solved in 2003 when Jacob Bekenstein published a "Tensor Vector Scalar" (TeVeS) theory (named after the three kinds of fields that are used). The tensor field describes Einstein's general relativistic gravity as it arises from the curvature of space-time. The scalar field gives the gravity extra strength at the low acceleration limit, such as in the outskirts of galaxies. The vector field is needed to cover another effect of gravity that we can observe, gravity acting as a lens enlarging the objects behind it; also called *gravitational lensing*. Although the TeVeS theory is still a 'bottom-up' theory which is specifically designed to match some phenomena, the connection between MOND and a relativistic framework encouraged many scientists to give it a second chance.

Chapter 3

A philosopher's approach

3.1 Philosophy of science in a nutshell

Philosophy of science addresses questions like "What is science?", "How is scientific research conducted and how should it be?" and "Is there something like universal truth and if there is, is conducting science the way to get near to it?" This chapter is meant to give a short overview in this field and describes the contributions of a handful philosophers which have had a major influence on the discussions about science in the last century.

Let's start with a standard, oversimplified view on science and how it is conducted. While there is no official standard view, most people have some idea of the scientific process (from popular literature or high school education) which is approximately like this:

> A scientific theory starts with an idea which is called a *hypothesis*. Such a hypothesis can emerge in a sudden bright moment to the scientist (an "eureka"-experience), but also be the result of experiments, however it should always explain something new. From this idea a theory is built. The new theory should follow the rules of logic and should be testable by investigation of facts. The truth of a theory depends on the truth of the facts it relies upon. The larger number of facts which agree with the theory the more solid the theory gets. If facts contradict a theory, it should be abandoned. If a scientist has collected enough facts to support his or her new theory, he or she will then publish these results. Many scientists will now start to reproduce the experiments done before and conduct new experiments to show the new theory does not work. If they succeed in this the theory is abandoned or at least altered to agree with the new facts. However, if it stands this test a new scientific theory is born.

As stated before, this view is oversimplified and the scientific process can in reality differ substantially from this. Here I will discuss the views of four very influential philosophers who have greatly contributed to the debate about what science is and how it is conducted. I will discuss their arguments against the standard view of science and on each others ideas.

3.1.1 Karl Popper

Karl Popper (1902-1994) is one of the philosophers who had a lot of criticism on the standard view of science. He developed his own theory of the origin and evolution of scientific theories. His first main point of criticism was the common sense view that a theory gets stronger when there is more factual evidence supporting it. According to Popper, the theories which acquire most supportive evidence, are also the most vague and less explanatory theories. An example is the theory of psychologist Adler who stated that a lot of human behaviour can be explained from a inferiority complex. Indeed all observed behaviour of test persons could be explained from such a perspective, but does this makes it a good theory? According to Popper, a good theory should not explain every phenomenon observed, but should make strong predictions that could easily be proved wrong. An example of such a theory is general relativity which predicted that light rays should be bent by strong gravitational fields, which was observed during the next solar eclipse. The bending of light rays was a risky prediction which could easily be falsified if the effect could not be measured. Therefore, Popper states, general relativity is a better theory than Adler's inferiority complex theory and not the other way around. The (use) value of a theory is determined by the falsifiability of its predictions.

Popper's second point of criticism of the standard model is that he didn't believe observations can be genuinely unprejudiced. Every observation is theory laden, in the sense that it always requires a set of notions, expectations or underlying theories. Without these, a person could see, but not observe. However, Popper also disagreed with relativists who stated that the choice for a proper theory is just a matter of taste, power or politics since observations are never genuine. Popper did believe that science is making progress and that bad theories could be replaced with better theories over time. In his scheme of theory making, a theory always starts with an unexpected result. On the basis of this a new theory is formulated which should make predictions that are falsifiable. Subsequently, all is done to test if the new theory can be falsified. If this succeeds, the (falsified parts of) the theory should be abandoned, if not, then this theory is temporarily proved right until such time as it is falsified. The problem in this scheme is that it is not always clear what facts justify the total abandonment of a theory if there exists no such thing as objective true facts. According to Popper the basis for facts are formulated by the scientific community, which should come to agreements which underlying theories and facts (for example the basics of optics or electromagnetism) are accepted.

3.1.2 Thomas Kuhn

One philosopher who has criticised Popper's model of theory formation is science historian Thomas Kuhn (1922-1996). He argued that in reality scientific processes are not as rational as in Popper's model, which completely ignored social and psychological influences. According to Kuhn a scientist in practice will not withdraw or abandon his or her theory easily once there is evidence found against it. He or she will more likely first try to repair the damage done by making small changes like fiddling with a fundamental constant, using an additional hypothesis to explain the exception observed, or argue that the observed fact is due to secondary effects. This is what Kuhn calls a period of normative science. In such periods, which should cover the largest part of scientific history, small puzzles are solved within the framework of the dominating theories of that time without altering these governing theories themselves. The combination of scientific theories, predictions and values that dominate the scientific landscape during such a period is called a *paradigm*. Only when the number of unsolved problems becomes too large will there be a period of change, called *revolutionary science* by Kuhn. In such a period the governing paradigm is abandoned and a new paradigm is accepted. According to Kuhn, this is however not a gradual process, the change in world view is so dramatic that a comparison of paradigms is impossible since other paradigms are written in a different "language".

Although Kuhn's theories completely changed the landscape of philosophy of science there is also a lot of criticism of his views. The most important point of his critics seems to be that scientific periods don't shift so suddenly, but that enormous amounts of time elapse between them. Although the world views of Aristotle and Newton (two major paradigms) are almost incomparable it should not be forgotten that many centuries and major cultural changes divide these two scientists as well. Despite this criticism Kuhn's work has been very influential and opened a new field of research; empirical-historical research of science.

3.1.3 Imre Lakatos

Imre Lakatos' (1922-1974) contribution to the philosophy of science tries to reconcile the ideas of Popper more with the research scheme as sketched by Kuhn. According to Lakatos, small *anomalies* (as unexplained apparent falsifications are called) or an extra ad hoc hypothesis which is needed to keep a theory alive should not immediately lead us to reject the whole theory. A theory can only be abandoned if there is a viable alternative [Ber03]. In contrast to Kuhn's work, it is possible according to Lakatos to weigh competing theories on the basis of various criteria and find the better alternative. A theory is thus not falsified by anomalies, facts or experiments, but by the existence of a competing theory with more explanatory force than the old theory. The new theory should meet three conditions [Bir98]:

- later theories should have some content not possessed by earlier theories - they should say more
- later theories should explain why earlier theories were successful; and
- later theories should have more corroboration than earlier theories

If all these conditions are met, Lakatos calls the theory *progressing*, otherwise it is *degenerating*. This approach is not just valid for single theories, the same method can be followed to evaluate paradigms which are called *research programmes* by Lakatos. Here, Lakatos' methodology of scientific research programmes is mainly interested in which theories have a good strategy of dealing with anomalies and which have not. The theoretical part of a research program is formed by a *hard core* and an *auxiliary belt*. The hard core of the theory will remain the same, although some changes might be made over time to the auxiliary belt, which is the list of assumptions and approximations that we need to make the theory work. On falsification of theories in research programmes Lakatos said:

> "It is not that we propose a theory and Nature may shout NO, rather we propose a maze of theories and Nature may shout INCONSISTENT" [Lak70a]

Additionally each research program has methodological components as well - *the negative and the positive heuristics*. The negative heuristic is the condition that the hard core of the theory should not be abandoned in case of anomalies. This is part of the methodology and thus accepted as a part of scientific process. New theories that show anomalies should be given a fair chance to adapt to them and advanced theories should not be abandoned until a rival program has developed that at least has the same explanatory power. The positive heuristic gives guidance how to handle anomalies that show up. This part of Lakatos' theory on research programmes is more debated, since in real cases it can be hard to point out the positive heuristic of a research program other than in very broad, general terms.

A comparative evaluation can be used both within one research program, by evaluating whether subsequent theories are progressive or degenerative, or in comparison to another research program. Research programs as a whole can be compared on their progressing or degenerating spirit as well, or in terms of their best theories. According to Lakatos' theory this is not possible at every moment, a new theory needs some time to be evaluated on its explanatory force. This explains why at many moments in time during scientific history competing theories were coexistent.

Lakatos' comparative approach forms the basis of the method used in this thesis for a comparison between the (cold) dark matter theory and MOND. A more detailed description of the method of comparison is given in the next section "Hypothetico-deductive evaluation of theories".

3.1.4 Bruno Latour

A fourth philosopher of science I should like to discuss briefly in this chapter because of his original approach to philosophy of science is Bruno Latour (1947 -). Latour was educated in philosophy, but he used research methodologies from anthropology as well in his studies of science. Only his objects of study were not some isolated Indian tribe in the Amazons, but scientists in a prestigious chemical laboratory in California, US. He registers how from a chaos of opinions, rivaling scientists, not entirely to be trusted machinery and never unambiguous research results still hard and tidy facts are drawn and published [DP00]. The traditional borderline between nature and society is nowhere to be found. Latour describes the scientific research method as an ongoing battle. The robust theories are those which survive, not because they describe the facts of nature, as we supposed in our naive description of science, but because the theory has the most allies. This however does not mean that science is simple a matter of politics, because in Latour's descriptions allies can be found in both human and non-human form. Everything supporting a theory is an ally: wind, microbes, bribe, electrons, politics, atoms and national interests [DP00]. No clear separations can be made between the different factors (human - non-human, natural - sociological, facts - values). A scientific fact can therefore never be separated from the network of allies which surrounds it.

Although controversial, Latour's observations of scientific work in progress have made a significant contribution to the way we in general, and many philosophers of science in particular, think about the scientific process.

3.2 Hypothetico-deductive evaluation of theories

3.2.1 Statements about truth and knowledge

As stated in the previous section, one of the leading questions in philosophy of science is: "Is there something like universal truth and if there is, is conducting science the way to get near to it?". Since in general the aim of scientific research is to obtain true knowledge, it is important to specify what exactly we understand of truth and how we think true knowledge is gained. This in itself is an interesting debate among philosophers, with one of the key differences whether true knowledge can be acquired on the world beyond the observable and on *theoretical terms* (linguistic entities which do not directly refer to observables). The main positions held by various philosophers are sketched in the diagram below. The different positions can be separated by asking some fundamental questions about knowledge and the world (after [Kui00]).

Question 1: Does a natural world that is independent of human beings exist?
Question 2: Can we claim to possess true claims to knowledge about the natural world?
Question 3: Can we claim to possess true claims to knowledge about the natural world beyond what is observable?
Question 4.1: Can we claim to possess true claims to knowledge about the natural world beyond (what is observable and) reference claims concerning theoretical terms ?
Question 4.2: Can we claim to possess true claims to knowledge about the natural world beyond (what is observable and) structure claims concerning theoretical terms ?
Question 5: Does there exist a correct or ideal conceptualization of the natural world?

Major positions in the philosophy of science will in general answer the first two questions affirmatively, but the answers to the other three questions very much depend on the position of the person questioned. To illustrate that many different positions are taken in the philosophical debate, the main positions that are held are sketched in the diagram below (after [Kui00]).

Question 3. $\Longrightarrow$ no $\Longrightarrow$ **empiricism**
$\Downarrow$
yes
$\Downarrow$
scientific realism

Question 4.1 $\Longrightarrow$ no $\Longrightarrow$ **referential realism**
$\Downarrow$
yes
$\Downarrow$
Question 4.2 $\Longrightarrow$ no $\Longrightarrow$ **structural realism**
$\Downarrow$
yes
$\Downarrow$
theory realism

Question 5. $\Longrightarrow$ no $\Longrightarrow$ **constructive realism**

⇓
yes
⇓

essentialist realism

3.2.2 Testing truth and success of theories: The hypothetico-deductive method

Although there are thus different visions to be held of truth and knowledge acquirement from the world around us, all like to answer some truth questions in relation to scientific theories. In this section I will discuss the hypothetico-deductive (HD) method as it has been further developed by Kuipers [Kui00]. By its designers Hempel and Popper it only was intended to provide an answer to the *truth question*: "Is a theory true or not?". Apart from truth questions, however, the (theory) realist will also be interested in other questions regarding theories, which are less absolute. He or she would like to know which facts the theory explains and which facts are in conflict with it. In general these kind of questions can be summarised as *the success question* of a theory. The HD method can also be used to answer these, more refined, questions. In the case just a truth question is addressed and theories are abandoned as soon as they are falsified we speak of *HD testing*. If, however, falsified theories are still taken seriously and further examined through success questions, we speak of *HD evaluation*. HD evaluation will thus keep taking falsified theories seriously, whereas HD testing will abandon a theory as soon as it is falsified. In this sense, HD evaluation fits in with the idea that science is fallibilistic, thus including the possibility of mistakes to be made. For a fallibilist all putative knowledge claims in science are temporary and revisable by further evidence [Nii]. In particular this means that a theory might be false, but still very close to the truth. This is in agreement with Lakatos' theory, because a falsified theory might still be the best available theory around, if no viable alternative is found. In my opinion this approach comes also closer to the scientific reality. In this report we will therefore focus solely on HD evaluation.

The general idea of the HD method is in harmony with the ideas of the philosophers Rudolph Carnap and Carl Hempel. Rudolph Carnap allowed theories to introduce theoretical terms, but required that a theory should be empirically testable: it should logically entail some empirical statements whose truth value can be checked by public observation. In HD testing a hypothesis is tested by deriving test implications from it in observation terms only, and checking whether these are true or false. There is always some background knowledge involved which is assumed to be true and there might be several auxiliary hypotheses to support the main theory. The HD testing method can be split into two separate steps, based on a macro- and a micro-argument. In the macro-step, a General Test Implication (GTI) is derived from the theory by means of logical-mathematical claims as is shown in the scheme below (after [Kui00]).

$$\begin{array}{l} Theory:\ X \\ Auxiliary\ hypotheses:\ A \\ Background\ Knowledge:\ B \\ \underline{Logico-Mathematical\ claim\ (LMC):\ if\ X,\ A,\ B\ then\ I} \\ General\ Test\ Implication\ (GTI)\ I:\ for\ all\ x\ in\ D[if\ C(x)\ then\ F(x)] \end{array}$$

From the theory a general fact about the world is derived which can now be tested. The outcomes of all the tests performed before a particular time, which are all partial answers to the success question, make up the evaluation report of X. This report mainly consists of:

- A set of individual problems, which covers every counterexample of GTI's of X
- A set of general successes, built up of all established GTI's of X

The method of the testing of a GTI itself is described in the micro-step. From the general test implication deduced from the theory, individual tests have to be designed which can be conducted. The first step is to find a situation which is an individual case of the GTI. The statement that the case tested is indeed one of the cases the GTI is valid for is called the *relevance condition*. Then, under the assumption of individual test conditions which have to provide the right environment to test what is meant to be tested and nothing else, the final experiment (or observation) will lead to an individual test implication. This can either be a counterexample, or individual problem of the general test conditional, or an individual success. The micro-step is clarified in the following scheme (after [Kui00]):

$$\begin{array}{l} General\ Test\ Conditional\ (GTC):\ G:\ for\ all\ x\ in\ D[if\ C(x)\ then\ F(x)] \\ \underline{Relevance\ Condition:\ a\ in\ D} \\ Individual\ Test\ Conditional:\ if\ C(a)\ then\ F(a) \\ \underline{Initial\ Conditions:\ IC:\ C(a)} \\ Individual\ Test\ Implication\ (ITI):\ F(a) \end{array}$$

Consequently, for every GTC an evaluation report can be made up, of individual successes and problems. An application of the HD method which leads to an evaluation report of individual successes and problems is called a micro-model of HD evaluation. In the case however of evaluating a theory as described above in the macro step, the micro step is just used for testing of the derived GTIs, not for evaluation. The individual successes are then, if possible, summarised in general successes. This model of evaluation using individual problems but general successes is called a asymmetric HD evaluation. Of course, a third reasonable possibility would be to also aim at generalisation of the problems and compare general successes and problems both at the macro level, creating a macro-model of HD evaluation.

In the reality of scientific practise not all test implications might be derived strictly deductive. However, there is no reason to inhibit the evaluation report from containing also these test implications.

From the three possible models for HD evaluation, the micro-model, the macro-model and the asymmetric model, the asymmetric model is the most attractive one [Kui00]. The combination of comparing general successes and individual problems seems to be the closest to what is observed in scientific practice and is the most suitable link to answering truth questions as well on top of the success questions.

Although all individual problems can, in a Popperian sense, be seen as falsifications of the theory, they don't always necessarily have to be treated this way. In the HD evaluation scheme presented above, Lakatos' methodology of "saving the hard core" of a research program can be very well defended and brought into practice, since the final conclusion of falsification depends on at least five factors used along the way.

- auxiliary hypotheses + background knowledge claims
- logico-mathematical claims
- observation presuppositions
- initial conditions
- decision criteria

As Kuipers states in "the threefold evaluation of theories":

> "Hence it will not be too difficult to protect a beloved theory from threatening falsification by challenging one or more of these suppositions" [Kui00].

3.2.3 Comparison of theories

What makes a certain theory better than another one? An obvious answer would be that the theory has to have the established strength of its rival and not add any new weaknesses. In the frame of a asymmetric HD evaluation this leads to the following formal interpretation of increasing success [Kui00]:

Theory Y is (at time t) at least as successful as theory X iff (at t):

- all individual problems of Y are (individual) problems of X

- all general successes of X are (general) successes of Y

and more successful (at time t) if in addition to this (at t):

- Y has extra general successes or X has extra individual problems

The statement that Y is more successful than X does not guarantee that this will remain the case, but the statement can never be reversed (if the established facts are not questioned), because X has more individual problems or less successes than Y.

In these criteria the ideas of Lakatos progressing/degenerating test for theories and research programmes is, although differently phrased, clearly recognizable.

To complement the core idea of empirical progress, also the following rule of theory selection should be applied [Kui00]:

Rule of success: When Y has so far proven to be more successful than X, eliminate X in favour of Y, at least for the time being.

Of course, in many cases there will be divided success between two theories, when both theories have successes or problems the other theory does not have. In that case a more refined qualitative method or even a quantitative method that counts the successes and problems of both theories can be used to sort out what is the best theory for the time being.

3.3 Arguments in Science

So far we have just been concentrating on empirical evidence supporting or rejecting scientific theories. But in general also a lot of other classes of arguments are used (explicitly or implicitly) in scientific practice as was argued also by philosophers of science like Kuhn and Latour. A very nice treatment and classification of non-empirical arguments is given by J.W. McAllister in his book *Beauty and revolution in science* [McA96]. Although McAllister claims that aesthetic arguments might not be everlasting and change with time, he presents five classes of current aesthetic properties. These classes are:

- Form of symmetry

  A theory is considered more beautiful if it shows invariance under certain changes. There are many forms of symmetry conceivable.

- Invocation of a model

  By invocation of a model is meant that the theory shows analogy with already familiar phenomena or theories.

- Visualizability/abstractness

  If a new theory has visualizability this means that there can be drawn some mental image of the experience that guides our understanding of what is going on. Often this mental image will be a metaphor. While visualizability is regarded as an argument in favour of a theory by one group of scientists, another group takes aesthetic pleasure however in theories that are *not* visualizable but abstract. Both can thus be regarded as aesthetical arguments of one class, despite the fact that they are the complete opposites of each other.

- Metaphysical allegiance

  One aesthetic form of argumentation in favour of a certain theory could be that it fits into the metaphysical world view of that time.

- Form of simplicity

  Arguments on the basis of simplicity of one theory versus another theory are also called arguments from the principle of parsimony, or arguments using Occam's razor. More specifically this principle states that a theory should make as few assumptions as possible. Popularly phrased: "All things equal, the simplest solution tends to be the right one". This principle is widely used in and outside of fields of science, but, like in all other aesthetic arguments, there is of course no universal guarantee that the Universe does indeed follow the laws of simplicity.

Another central topic in the book is the role of beauty in scientific revolutions. McAllister claims that although a lot of scientists believe that theories should have a certain degree of beauty, these aesthetic criteria are based on the aesthetics of successful theories of the time. Theories that are developed according to these aesthetic criteria therefore can not be seen as revolutionary. McAllister elaborates his sense of a revolution in science as follows:

> "A scientific revolution occurs when theory choices performed on empirical criteria depart from those performed on the aesthetic canon. At such times, the aesthetic canon escapes from the shadow of empirical criteria: it exercises a conservative function, advocating the retention of theories, showing familiar aesthetic properties and the rejection of their new, aesthetically innovative competitors." [McA96]

In a period of revolution scientists are divided into two camps: those who state that the empirical correctness of a theory is most important and support therefore the new thinking, and those who hold on to their aesthetic criteria and therefore do not believe in the new ideas. This scientific practice is also the reason that aesthetic criteria are not everlasting and that they too change with time. A clarifying example of a scientific revolution given in the book shows the break with the old aesthetic (Aristotelian) principles by Kepler, who deduced from empirical data that the orbits of the planets around the Sun are elliptical.

Although the next few chapters are dedicated to the more empirical arguments in favour of and against both theories, in the final comparison also attention will be given to their aesthetic values.

Chapter 4

Problems and successes of MOND

> "..if one chooses to modify Newtonian dynamics or gravity in an ad hoc fashion, the set of alternative possibilities is large. (..) To be credible, an empirically based alternative to dark matter should at least provide a more efficient description of the phenomenology. Any viable alternative should account for various aspects of the observations of astronomical systems with as few additional parameters as possible. A second, but less immediate, requirement is that the suggested alternative should have some basis in sensible physics – it should make contact with familiar physical principles or at least a reasonable extrapolation of those principles" [SM02].

In this section an overview will be given of the strengths and weaknesses of MOND as a theory. First, various topics related to the theory are described in more detail. Just the *empirical* successes and problems are discussed in this chapter, a broader comparison will be given in Chapter 7. After the discussion of each topic, the main conclusions are summarised briefly. A more schematic overview of these summaries is given in the evaluation report of the HD evaluation of MOND in the second section of this chapter. In this report the problems and successes of MOND as a scientific theory are listed. A distinction is made between *general problems or successes* that are generally accepted to be valid for all cases and *individual problems or successes* that are derived from just one test case.

4.1 Galactic rotation curves

> "The fact that there is an algorithm – MOND – that allows the form of individual rotation curves to be successfully predicted from the observed distribution of detectable matter – stars and gas

– must surely be seen, at the very least, as a severe challenge for the dark matter hypothesis" [SM02].

One of the greatest, maybe even the most outstanding, phenomenological successes of MOND is the fitting of rotational velocities in spiral galaxies. As discussed in the first chapter of this thesis, the rotational velocities of stars and gas clouds in the outer regions of these galaxies do not match with the observed luminous mass inside. Assuming that MOND is the right solution to this problem, predictions can be made for *rotation curves.* These map the rotational velocities of matter as a function of the distance to the centre of the galaxy. One example of such a rotation curve for the Andromeda galaxy was shown in Figure 2.1. For every individual galaxy, the starting point for fitting such rotation curves is the observed distribution of stars and gas. Subsequently the MOND formula is applied to this known mass distribution to get a rotation curve for the whole galaxy.

Because the peculiarly high velocities of stars in the outskirts of galaxies were one of the main reasons to develop MOND in the first place, it is not surprising that the overall shapes of the predicted rotation curves fit the observations. Especially, it was shown in Chapter 2 that MOND by definition predicts flat rotation curves in the outskirts of galaxy and galaxy clusters where they are well inside the MOND regime. It is however remarkable that MOND theory rotation curves fit not only the rough, flat trends of galaxy rotation curves but in many cases fit the peculiarities of an individual galaxy as well. In (cold) dark matter theory these peculiarities are thought to result from the unique formation and merging history of a galaxy, but MOND seems to fit these features better without assuming any unique history [SM02].

The success of MOND to fit the shape of rotation curves often in much detail basically shows that the overall rotation curve of all mass inside a galaxy is very sensitive to the distribution of the luminous matter inside. Because MOND does not assume any dark matter content the total mass inside a certain radius can, certainly within the Newtonian limit, be regarded as a scaling of the luminous matter. If there is a local under- or overdensity in the luminous matter, this will reflect in a dip or bump in the rotation curve. In dark matter theories this relation between luminous and total matter is harder to explain, because there is no physical reason for dark matter (which is thought to be a much more dominant influence to the final shape of the rotation curve) to follow the luminous matter so accurately.

Besides parameters within the theory itself, like the form of the interpolation function, μ, and the acceleration constant, a_0, MOND fits rotation curves using only one fitting parameter, which is the mass of the stellar disk. This mass is approximated assuming some constant value for how many and how massive stars in general produce a certain amount of light we can observe, the *mass-to-light* ratio. This fitting parameter has some freedom, since not all galaxies are built up out of the same sort of stars so the mass-to-light ratio can vary slightly from galaxy to galaxy. However, in general the value of the mass-to-light ratio is by theory constrained, which means that in fitting MOND rotation curves even the most free parameter is not entirely free. There are two other terms that have to be known, the inclination of the galaxy, which is the angle under which we observe it, and the distance to the observed galaxy. But both these parameters can be measured independently with other methods [MB98a]. Strictly speaking there is one extra free parameter involved in MOND rotation curve fitting, which is the form of the interpolation function μ. This is however constraint for the whole sample of galaxies for which rotation curves are fitted and not used as a free parameter in each separate fit. Bekenstein notes that "In disk galaxies MOND is unquestionably more economical, and thus more falsifiable, than the DM paradigm" [Bek06]. He states that dark matter modelling usually needs at least two other free parameters to get a comparable fit to the MOND fitting. These extra parameters are not constrained by any data independent of the rotation curves themselves, which makes the whole fit less well constrained [MB98a].

4.1.1 Elliptical galaxies

There are many different types of galaxies in the Universe. In the larger galaxies differentiation can be made between elliptical and spiral galaxies, referring to their form. Spiral galaxies, like our own Milky Way, are flat, the stars are arranged in a disk, and quickly rotating with a number of spiral arms. Elliptical galaxies have less obvious features (no high concentration of stars in a disk for example) and are ranging from almost spherical to more flattened shapes. Figure 4.1.1 shows an example of both types of galaxies.

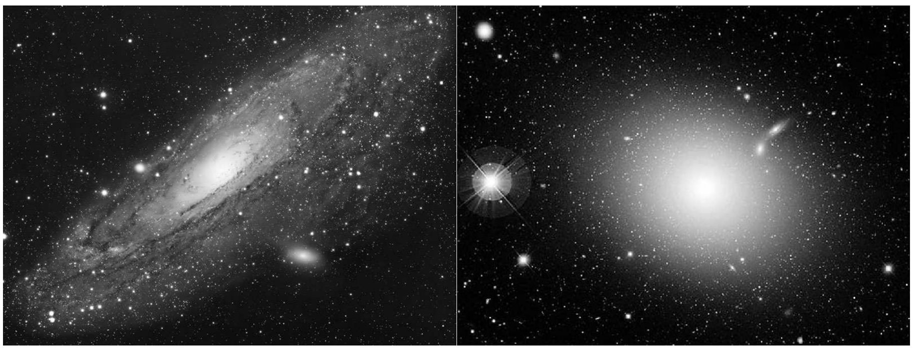

Figure 4.1: Left: Spiral galaxy Andromeda (Astronomy Picture of the Day, Copyright: Robert Gendler). Right: Elliptical galaxy M87 (Astronomy Picture of the Day, Copyright: Anglo-Australian Telescope Board)

In spiral galaxies, the velocities of especially the hydrogen clouds can be measured out to large radii away from the centre, which is perfect for measuring rotation curves. For ellipticals however, there is very limited data available, because we often don't know what orbits stars or gas follow and velocities can not be mapped at many different radii. Consequently, the data that we have does not probe the regime of the galaxy were the MOND laws should take over from Newtonian physics. Therefore elliptical galaxies can not provide a very good test. The only prediction that can be made is that because the observed parts of the massive ellipticals are not in the MOND regime, MOND predicts that the movements of the matter should be completely predictable from Newtonian physics and thus from the amount of visible matter. And indeed, in some elliptical galaxies dark matter is not needed in the (cold) dark matter models [Ber94].

4.1.2 High and low surface brightness galaxies

Besides the differentiation between spiral and elliptical galaxies, further subclassifications are made within these two different classes. Spiral galaxies can be very centrally concentrated, with a lot of mass in the centre and a small disk, or more extended with very large disks which tend to be less bright. Within the MOND theory the value of a_0 can be linked to a certain value of a parameter called the *surface density*, which measures the mass within a certain area in the disk of a galaxy, or the denseness of the matter in the disk. Wherever in a system the surface density of matter drops below this typical value set by a_0: Σ_M, the gravitational behaviour of the mass should also go from Newtonian to the MOND limit. In spiral galaxies like our own Milky Way the disk is dense enough that this only happens really in the outskirts, but in the 1980's a population of spiral galaxies was discovered for which the majority of the disk of the galaxy was in the MOND regime. These galaxies are called low surface brightness galaxies (LSB), because the low density disks are also less bright, as opposed to the more frequently observed high surface brightness galaxies (HSB). The rotation curves of these galaxies look really different from those of HSB galaxies as can be seen in Figure 4.2.

For HSB galaxies the velocities reach the flat part of the rotation curve very rapidly not far from the centre of the galaxy which MOND physics is able to fit well [San96, San07]. For LSB galaxies however, MOND must give not only the right value for the flat part of the curve, but also match the gradual rise toward it. The theory was never designed to do so, although Milgrom had in 1983 made some predictions about what LSB rotation curves would look like. The fitting of LSB rotation curves provided therefore a strong test for the theory. Indeed, as was showed in a paper by McGaugh & de Blok in 1998, MOND succeeded to fit a sample of fifteen LSB galaxies very well. Nine of the galaxies showed a perfect fit using only the mass-to-light ratio as a free adjustable parameter, for six of them they had to change the angle of view a little bit.

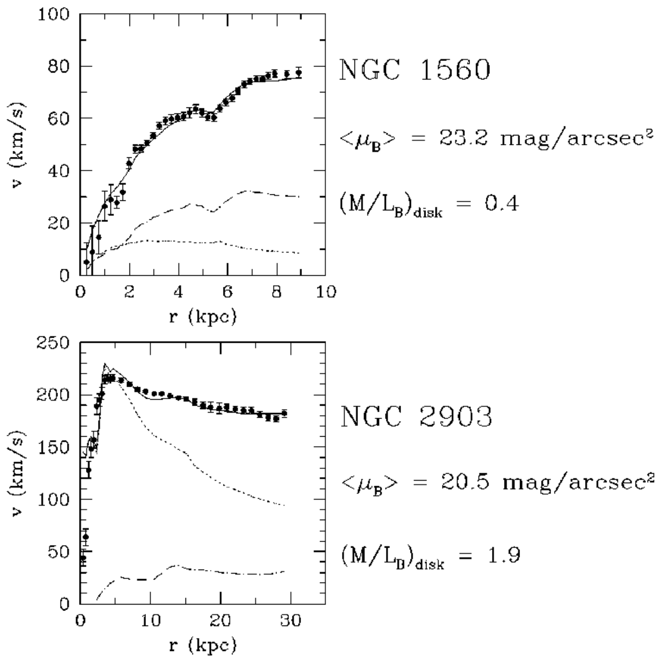

Figure 4.2: A rotation curve for a low surface brightness galaxy (top) and a high surface brightness galaxy (bottom). The points show the velocities observed of stars and gas. The dotted and dashed lines are Newtonian rotation curves for the gas and visible components of the disk and the solid line gives the MOND prediction for a rotation curve. The only free parameter used is the mass-to-light ratio of the visible component, which is given as well. (From [SM02].)

The confirmation of all facets of Milgrom's predictions for these LSB cases is maybe the strongest evidence in favour of MOND theory. As will be discussed in the next chapter, the (Cold) Dark Matter paradigm had (initially) much greater difficulty in explaining the shape of the rotation curves of low surface brightness galaxies [MB98].

4.1.3 Galactic Rotation Curves – Conclusions

The fitting of the shape of rotation curves, and sometimes even features within these curves, are a great success for MOND. Especially because also a good match could be made for low surface brightness galaxies, a class of galaxies that were discovered after the foundation of MOND theory itself. MOND in general uses less free parameters to make equally good fits compared to (cold) dark matter theory.

4.2 Clusters of galaxies

In the previous sections we have seen that MOND in general works very well on galaxy scales. The problem which is most referred to for MOND is however not the dynamics on galaxy scales but on cluster scales. MOND can not account for the mass discrepancy in rich clusters of galaxies. Within such clusters there is missing mass from a dynamical analysis, as was discussed in the first chapter. But because in these clusters of galaxies, certainly in the inner regions, the observed acceleration is not below the critical value of a_0 the cluster dynamics stays in the Newtonian and not in the MONDian regime. MOND physics can therefore not give any explanation for the observed lack of mass. The discrepancy between the observed mass and the dynamical mass is of the order of a factor of three. This means that MOND clearly also requires the presence of dark, undetected mass here, although the amount needed is still significantly less than in the conventional (cold) dark matter theory [San07a]. MOND scientist Bekenstein (2006) discussed this issue as follows:

> "The optimist will stress that MOND has alleviated the discrepancy without even once over correcting for it; the pessimist will view this finding as damaging MOND's credibility. But one should keep in mind that clusters might contain much invisible matter of rather prosaic nature, either baryons in a form which is hard to detect optically, or massive neutrinos. However the option that clusters contain non-baryonic cold DM between the galaxies, while logically possible, seems hardly justifiable in view of MOND's overall philosophy" [Bek06].

To fix the problem with massive neutrinos is an interesting solution. Although some people think MOND should not get in touch with dark matter of any kind, we do know that neutrinos exist and it has been established by experiments that neutrinos do have a certain (small) mass. According to Sanders (2007), neutrinos with a mass of 2 eV would be a good candidate for missing mass in clusters. A mass of 2 eV is allowed, because it is still somewhat (but not much) below the upper limit which was experimentally given. Because neutrinos are a form of hot dark matter they are not expected to group together in galaxies, but they could reside in clusters of galaxies which have a much greater gravitational potential. An interesting experiment that will be conducted in the next decade that might solve this debate is the KATRIN (Karlsruhe Tritium Neutrino) experiment. This experiment will measure the mass of the neutrino very accurately. While the experiment will not falsify MOND if the mass of the neutrino is found to be much less than 2 eV, for there are more candidates to solve the missing mass in clusters, like baryonic hot clouds, it will be a boost for the theory if the mass is found to be around 2 eV.

A specific example of the debate if MOND could account for the missing mass in clusters is the famous Bullet cluster (further discussed in the next chapter). The matter is discussed by Sanders [San07a]:

> “..observations of the famous “bullet cluster” (Clowe et al. 2006) are now presented as definitive evidence for non-dissipative dark matter in clusters of galaxies and, by extension, as evidence against MOND. (...) But in fact, the bullet creates no *additional* difficulties for MOND; the quantity of dark matter required is consistent with that suggested by the previous analysis. What the bullet cluster adds (and this is a significant addition) is convincing evidence that the dark component cannot be dissipative like the extended X-ray emitting gas.” [San07a]

Dissipative here means that the matter is exchanging energy (or heat) with the surroundings. The bullet cluster observations did not find any extra dark matter, but they did show that the dark matter required here has to be of a special form, namely non-dissipative, which puts an extra constraint and rules out many baryonic dark matter alternatives. Still, massive neutrinos would be good candidates to solve this problem within MOND.

However, even taking into account the massive neutrinos Angus et al [AFB07] find that an additional (baryonic) yet undetected mass is still required in several galaxy groups and clusters. This additional baryonic mass could for instance be in compact and cool clumps of gas [AFB07].

An additional escape is provided by Sanders [San06]. From MONDian related cosmology also a dark matter particle can be created that can be trapped in clusters, but not in galaxies. The advantage of this solution is that the particle follows from the theory itself, but it will be introducing dark matter into MOND.

4.2.1 Clusters of galaxies – Conclusions

The observed missing mass in clusters of galaxies is a problem for MOND. The mass needed to keep the cluster stable with MOND physics is still three times larger than the observed mass in the cluster. A solution to this problem might be that neutrinos (which are known to exist and have a small mass) have a mass of around 2 eV. Because neutrinos are thought to reside in clusters of galaxies and not in individual galaxies themselves this is in agreement with the observations. However, this problem has made it difficult to consider a Universe with MOND physics and no influential form of dark matter at all.

4.3 Dwarf galaxies

As we have seen before, galaxies come in many different forms, but they also exist in many different sizes. Additional to the massive galaxies, which we know better because they are brighter and therefore easier to observe, there also exists a class of smaller galaxies called *dwarf galaxies*. Often these dwarfs are seen as companions of larger galaxies, the most well studied examples are the dwarfs associated with our own larger galaxy, the Milky Way and our neighbouring galaxy Andromeda.

4.3.1 Tidal dwarf galaxies

In this section a very typical form of dwarf galaxies will be considered. Occasionally, galaxies in the Universe do collide with each other. If two galaxies come close to each other the gravity of both systems will force them to collapse. In fact our own Milky Way is on collision course with the Andromeda galaxy right now, although it will take another few billion years for them to actually meet each other. In the collision of larger galaxies, material can be slung out from their most crowded regions and under force of its own gravity this material can contract and form a dwarf galaxy. Such dwarf galaxies are called *tidal dwarf galaxies*. In the currently holding (cold) dark matter theory these galaxies should be mostly free of dark matter. This statement was recently tested by Bournaud et al (2007) for three tidal dwarfs around galaxy NGC5291 and they found that, contrary to their expectations, the tidal galaxies were measured to be at least twice as massive as their observable mass content, both from their high radial velocities around the main galaxy and from their own rotation curves.

Although it is hard to solve this problem within standard CDM theory (see next chapter) the observed rotation curves and velocities can be explained by MOND very naturally without assuming any additional unseen matter [GFC07].

4.3.2 (Velocities of) dwarf galaxies

One issue of debate between MOND supporting astronomers and those who are in favour of dark matter theory, is whether MOND can correctly predict the properties of small galaxies or dwarf galaxies, in particular those around the Milky Way which are best studied. The dwarf galaxies, and in particular the spherical shaped ones that we know of, are known to have large mass discrepancies [Mat97]. The question is whether MOND alone can deal with these differences between the observed mass and the strength of the gravitational field. It is slightly harder to test dwarf galaxies than larger spiral ones, because the stars do not move neatly in a disk. Gerhard & Spergel concluded in 1992 from their research on dwarf galaxies that MOND fails in this regime, because it could not give reasonable values for the mass-to-light ratio of two dwarf spheroidal galaxies in particular: Fornax and Ursa Minor. However, McGaugh and de Blok [MB98a] argue that the error bars on these measurements should have been larger and that with more recent data "there is no evidence that clearly contradicts MOND in the data for dwarf spheroidal galaxies" [MB98a].

More recent measurements of properties of the Draco dwarf provide also difficulties for MOND. In order to fit the velocities of the individual stars an unrealistic value has to be taken for the mass-to-light ratio. This result does not immediately falsify MOND. The authors stress that several possibilities remain open, like the possibility that a_0 is not truly universal, but takes different values for different classes of objects. Also, in their results the gravitational pull of the much larger Milky Way galaxy was not taken into account, which may be important in MOND [LMP06].

Subsequently the velocity distribution of the dwarf galaxies around several larger galaxies is a matter of debate. Klypin and Prada [KP07] argue that MOND "fails badly" to model the observed distribution and velocities of dwarf galaxy satellites and that the observational data strongly favours the standard cosmological model. On the other hand, in reaction to this paper Angus et al [ASZ07] claim that MOND consistently reproduces the found velocities and that the former analysis of Klypin and Prada suffers from "fairly crude assumptions". Both papers accuse the rival authors of not handling the physics in their models well enough.

4.3.3 Dwarf galaxies – Conclusions

The results from the study of three tidal dwarf galaxies provides an individual success for MOND, since the rotation curves are easy to explain within a MOND framework. The reason this is an individual and not a general success is because only three tidal dwarfs have been tested within the same system, there is no confirmation that this result will be generalised toward more, and maybe even all, tidal dwarfs systems. The results on dwarf galaxies in general, their dark matter content and velocity dispersion, is quite ambiguous and hard to interpret. In general it seems that MOND has more difficulty in explaining the observed values. The case of Draco forms an individual problem for MOND.

4.4 Cosmology

While MOND theory started as an ad-hoc hypothesis, dealing with the unexpected flat form of galaxy rotation curves, the theory has been given more of a backbone quite recently now it is reconciled with general relativity through the Tensor-Vector-Scalar (TeveS) theory of Bekenstein. TeVeS actually can be described as a family of theories, since there still is some freedom in choosing functions. The main problem with TeVeS theory is that it is specifically designed to solve some problems and that it does not start from one grand principle (in contrast to for instance the general relativity theory of Einstein). Another objection is that the form of the interpolation function, μ and the value for the important acceleration constant a_0 have to be put in by hand and do not follow from the theory itself. Remarkably, a_0 does seem to have a cosmological scale, since the experimental set value is very close to cH_0, the multiplication of two important cosmological constants: the speed of light and Hubble's constant determining the expansion of the Universe. Especially because a_0 seems to be on this interesting cosmological scale, one would expect the underlying theory to give a physical explanation for this relation. On the other hand, the nuisance of lack of uniqueness of solutions, does allow some flexibility in the search for the right theory [Bek06]. Obviously still the motivation for TeVeS arises from phenomenology rather than pure theory.

Additionally to general relativity MOND theory will also have to come to terms with the *Cosmic Microwave Background* (CMB) spectrum, which is nicely fit by the (cold) dark matter paradigm (see also next chapter).

The CMB spectrum really is the imprint of what we still see from the initial circumstances not long after the Big Bang. The most difficult problem for Big Bang theory, when it was still debated a couple of decades ago, was to explain how it was possible that from an initial soup of particles in an expanding Universe large structures like galaxies are able to form. To make this happen, the very early Universe needed already some tiny fluctuations in the density of matter, that could then grow larger and larger with time. In the CMB, the light that reaches us from 300.000 years after the Big Bang, indeed these tiny fluctuations can be seen! (See Figure 4.3). To be a fully serious contestant of (cold) dark matter theory MOND had to be reconciled with these important findings as well. Skordis et al. showed that TeVeS can be consistent with the CMB spectrum and today's spatial distribution of galaxies if some dark matter is allowed, namely in the form of massive neutrinos and if there exists a nonzero cosmological constant [Sko06]. In addition to this Hao and Akhoury ([HA05]) showed that with an appropriate choice of function the scalar field in the TeVeS theory can play the role of dark energy. Zhao maintains that cosmological models can be run which show the right timescales for structures to form without assuming dark matter or even dark energy [Zha06]. This is a first answer on a key question regarding MOND cosmology: Will MOND be able to grow structure in the Universe fast enough? The reason this is a concern is because in a MOND Universe only the baryonic matter can make the first fluctuations grow. In (cold) dark matter theory the baryonic content gets "help" from the dark matter content to keep the first fluctuations growing. Will MOND structures grow fast enough to form whole galaxies at the times we observe them? While the first steps in answering this question are thus taken and they seem to provide an affirmative answer, this topic has to be studied in much more detail in the coming years.

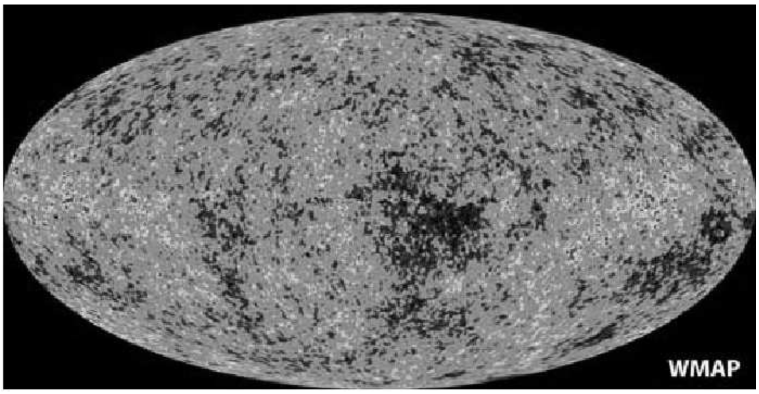

Figure 4.3: The Cosmic Microwave Background radiation as seen by the WMAP satellite. This figure shows the whole sky. What is important are the small fluctuations (shown here in darker and lighter grey) in temperature tracing density in the early Universe approximately 300.000 years after the Big Bang.

4.4.1 The way structures grow

Apart from the question whether structures in the Universe like the galaxies will be in place in time, there is also the question what they will look like. By changing the underlying model for structure growth, predictions can be made as to which physical processes will change and what effect this will have on the appearance of the structures themselves.

Bar formation in disk galaxies

In some disk galaxies we observe not only the disk, but we see that within the disk another structure has formed: a bar. When simulations are performed of disk galaxies it was found that it was remarkable easy to construct bar-like features, in fact it was really hard to prevent them from forming. But observationally we see that a lot of disk galaxies do not show a bar at all. Dark matter halos were originally also intended to prevent bar formation in every disk galaxy. They make the disk more stable by putting a spherical halo around it. In MOND also the stability of disks is enhanced, but not in exactly the same manner. If the disk comes in its outskirts the MOND physics regime, the degree of stability saturates. In general this means that in MOND theory bars can form more rapidly in the early universe, but they weaken with time [Bek06]. This effect has not been tested thoroughly enough to give some results, but it is a prediction of MOND that can observationally be tested in the future.

Formation of galaxies and mergers

There are several other physical processes that change their speed as well if simulations are performed using MOND physics. In galaxy interactions which eventually merge together to form one large galaxy the whole process slows down, because there is less matter interacting [Tir07, NLC07]. The end product of such a merger does however look very much the same from the end product in a dark matter simulation [NLC07]. In general galaxy merging is less effective in MOND than in (cold) dark matter simulations. This and the slower speed of merging might form a problem for MOND, because in general astronomers believe that merging is an important way to form larger and larger galaxies. On the other hand, the precise number of mergers a galaxy experienced in its life is still unknown. This parameter could help to discriminate between the two models. Furthermore, the slow merging might explain the existence of compact galaxy groups which should have merged long ago in the cold dark matter paradigm [Tir07].

The existence of even smaller objects orbiting around dwarf galaxies, *globular clusters* (tight clusters of stars) are unexpected in MOND simulations, because the smaller systems should be swallowed by the dwarf galaxy very rapidly. Yet we do know there exists at least one such system, the Fornax dwarf galaxy. Though problematic for MOND, we will see in the following chapter that this very same system is also a problem for (cold) dark matter theory.

A lot of other, more speculative, effects are also possible within MOND theory. For instance, Sanders (2007) mentions that it might be possible that many galaxies show strange ring-like features in gravitational effects when the strength of the gravitational field is in a transitional region between the Newtonian and the MOND limit. How strong these features are, will also depend on the form of the interpolation function μ between the two limits [San07b].

4.4.2 Cosmology – Conclusions

From the extension of MOND with TeVeS cosmological models can be made with MONDian physics. Although the first results seem promising, the question whether MOND can grow structure according to the current observations is still largely unanswered. Predicted is that bars will form more and more rapidly and that merging is less effective and slower. Whether this can be seen as a problem for MOND is still unsure. The globular system of Fornax forms an individual problem, because the MOND physics would predict the globular clusters to have sunk in by now. In general however, the connection of MOND with cosmology is definitely a promising step forwards.

4.5 Gravitational lensing

Another issue is *gravitational lensing.* Because general relativity predicts that light will be bent in the vicinity of a strong gravitational field, very heavy objects can cause strange distortions of images. If a galaxy is viewed for example that is behind another galaxy, the mass of the foreground galaxy can bend the light such that we see the galaxy behind it in a very distorted way, or sometimes we even see multiple images of it, or a ring around it. These effects are illustrated in Figure 4.4. Gravitational lensing was seen as one of the greatest successes for the (cold) dark matter theory, since the galaxy which was acting as a “lens” always proved to be heavier than the observable mass inside that galaxy. However, when MOND is incorporated into a general relativistic context, gravitational lensing is also possible in MOND theory. There are some predicted differences in MOND-lensing versus dark matter lensing that can be checked observationally. The most prominent one is that the form of the lens will be strongly correlated with the distribution of luminous matter, whereas in dark matter theory the dominant dark matter halo, and thus the effect of the lens, is thought to be more spherical [SM02].

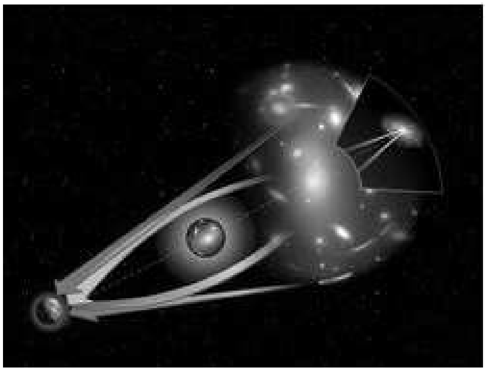

Figure 4.4: This figure illustrates the way a gravitational lens works. A galaxy (middle) is distorting the light from a distant galaxy, which is shown in its original form in the right upper part of this figure. The distorted image that we really see from Earth, because of the galaxy right in front of the distant galaxy is shown in front of the original background galaxy. You can see that gravitational lensing can not only change the shape of the galaxy, it can also make multiple images from one object. (Figure from http://faulkes-telescope.com)

From models and observations of three well known gravitational lensed clusters Takashi and Chiba [TC07] conclude that even within MOND a dark matter halo is needed to explain the observed results. While they mention several uncertainties in their study, they also note that "we find that there is some tension between the lower bound of the neutrino mass in neutrino dark halo model in MOND and the upper bound by experiments" [TC07]. In other words, the neutrino masses they needed come really close to the upper limit given by neutrino mass determination experiments.

A more severe problem for MOND theory and lensing is provided by Ferreras et al. [FSF07]. They investigated gravitational lenses of single galaxies. Also in these lens examples they found that to mimic the observed properties they needed a significant amount of dark matter, even within MOND. In this case the existence of heavy neutrinos can not solve the problem, because neutrinos are too hot to cluster in individual galaxies. The strength of these results depends on whether there can be found any other effects, like other nearby galaxies that influence the gravitational acceleration. However, if these results are confirmed, these so-called strong lenses form a serious problem for MOND.

4.5.1 Gravitational lensing – Conclusions

Although the general effects of gravitational lensing are also found in TeVeS theory, there are some (possible) problems. Observations of gravitational lensed clusters seem to be still consistent with MOND, although the needed mass for neutrinos reaching on to the experimental upper limit. For gravitational lenses in galaxies, one study also reports problems and here massive neutrinos can not help. This single study therefore forms an individual problem for MOND. Furthermore, the prediction is made that lenses will be less symmetric in MOND.

4.6 Physical relations

4.6.1 The Tully-Fisher relation

The *Tully-Fisher relation*, as described in an article by Tully and Fisher in 1977, describes an observed linear relation between the luminosity (the amount of light) from a spiral galaxy and the value for the spin of the galaxy, or the velocity width (which is also the amplitude of the flat part of the rotation curve). The real luminosity of a galaxy is sometimes hard to measure, because we see it from a distance. Even if a galaxy is very bright, if it is further away, it will appear weaker. To know what the real luminosity is, we need to have an idea of the distance of the galaxy as well. When Tully and Fisher discovered the real luminosity of a galaxy and the velocity width were two related quantities, they realised this could also be used to estimate the distance once the apparent luminosity (as seen from us) and the velocity width are measured. While this was a very useful tool, since distances can be particularly hard to measure in astronomy, the physical reasons why the two quantities might be so tightly related remained rather unclear.

In physical terms, the relation between luminosity and velocity width means there has to be some physical correlation between the stellar mass of a galaxy (responsible for the light emitted) and the total mass felt by the stars (responsible for the movements and thus velocities of the stars). In MOND theory there is no dark matter, thus it is no surprise that the amount of luminous matter and the total felt gravity should be related, since the last is directly constituted by the first through the MOND laws. A Tully-Fisher relation even follows straight from the MOND formulas in the following way:

In the MONDian limit: $\vec{g} = \sqrt{g_N a_0}$, with $g_N = \frac{GM}{R^2}$

For circular orbits around a point mass, M, we can balance the acceleration above with the centripetal acceleration as shown before in Chapter 2. In the MOND regime:

$$\frac{V_c^2}{R} = \sqrt{\frac{GM}{R^2} a_0} \tag{4.1}$$

Therefore the asymptotic constant rotational velocity independent of R (which is the value of V_c as measured in the flat, outer part of the rotation curve) will be:

$$V_c^4 = a_0 GM \tag{4.2}$$

In MOND theory a_0 is thought to be a fixed universal constant which does not vary in individual galaxies. By fitting a lot of rotation curves for various galaxies with different properties, the best overall fitting a_0 can be determined. The obtained value from this method is around 1.2 x 10^{-10}ms^{-2} [BBS91]. This value is found to agree well with the value needed for the slope of the observed Tully-Fisher relation [Bek06]. Although the role of a_0 is different in the two subjects, MOND succeeds in tying the two together.

4.6.2 Faber-Jackson relation and the fundamental plane

In analogy with the Tully-Fisher relation in spiral galaxies, also in elliptical galaxies the luminosity of the galaxy and the range of velocities from the individual stars, called the *velocity dispersion*, are related. This relation is called the *Faber-Jackson relation*. Subsequently there is also an observed relation between the (effective) radius of the galaxy and the luminosity in elliptical galaxies. The threefold relation of velocity dispersion, effective radius and luminosity for elliptical galaxies is in astronomy often referred to as the *fundamental plane*.

Due to their higher densities, elliptical galaxies are almost fully in the regime of Newtonian laws and not in the MOND regime. In this case the luminous matter dominates the physics of the galaxy, which means that luminosity and mass are related to each other. Once this connection has been made it is fairly easy to make a further, physically motivated explanation for the relations between luminosity, velocity dispersion and effective radius from ordinary physics. This relation thus holds both in MOND and in general Newtonian physics. However, some tilt has been observed in this linear relation that can only be explained in MOND. The outskirts or low surface brightness parts of the ellipticals, which might be in the MOND have different gravitational laws and may therefore be responsible for this tilt [Sca06]. In the (cold) dark matter scheme, this connection is harder to motivate as we will see in the next chapter.

4.6.3 Freeman and Fish laws

As discussed above in the case of low surface brightness (LSB) galaxies, MOND theory predicts that there is a certain surface density related to the value of a_0: Σ_M. Below this value, galactic disks are found to be more stable. In 1970 astronomer Ken Freeman found that most spiral galaxies have a surface brightness very close to one particular value which was later called the *Freeman value*. Although with the discovery of LSB galaxies in the 80s it was shown that the surface brightness can be below this value, the upper limit still holds. In MOND this observed fact has again some relation with a_0 since the Freeman value for surface brightness corresponds to the value of surface brightness expected for a galaxy that has surface density around Σ_M. Again, a similar law has been observed for elliptical galaxies, called the Fish law.

Also the surface densities in even smaller (clusters of stars or clouds within a galaxy) or larger systems (clusters of galaxies) are found to be near the typical MOND surface density Σ_M, set by the value of a_0 [SM02].

4.6.4 Physical relations – Conclusions

Due to the direct connection MOND makes between the observed mass and the gravitational field, physical relations between the dynamics and the phenomenology of systems are given a physical foundation. The value of a_0 seems to tie all these independent physical laws together. A particular success in the case of MOND is the observed Tully-Fisher relation which directly follows from the gravitational laws. Also the fundamental plane and its tilt and the Freeman and Fish laws are given a more physical background as to why they are observed in this way.

4.7 Evaluation Report

General successes

- MOND explains galactic rotation curves often into great detail using effectively just one free parameter (§4.1)
- MOND successfully predicted the shape of LSB galaxy rotation curves, before these were actually discovered (§4.1.2)
- Recently MOND has made contact with general relativity through TeVeS and therefore it can be used in simulations (§4.4)
- It ties together observed properties of several spiral and elliptical galaxies of various sizes to the value of a_0 by predicting the Tully-Fisher relation and explaining the Freeman and Fish laws, the Faber-Jackson relation and the fundamental plane (§4.6.1, §4.6.2, §4.6.3)

General problems

- Missing mass in clusters. While this partly can be explained by massive neutrinos, additional baryonic mass is still needed (§4.2)
- TeVeS is still a bottom-up theory. Both a_0 and the interpolation function μ have to be put in by hand. (§4.4)
- Galaxy merger timescales might be too long (§4.4.1)
- Gravitational Lensing in systems require additional mass even with MOND (§4.5)

Individual successes

- At least one system of tidal dwarfs can be explained without dark matter (§4.3.1)

Individual problems

- Velocity curves of dwarf satellites, in particular Draco (§4.3.2)
- The globular cluster system of Fornax (§4.4.1)

Predictions

- Galaxies form bars more rapidly and more often (§4.4.1)
- Merging of galaxies is less effective and slower (§4.4.1)
- Lensing effects will be less symmetric and more following the shape of the observed matter distribution (§4.5)

Debated Matters

- Do velocity curves and distributions of dwarf galaxies form a problem within MOND? (§4.3.2)
- One study shows that additional mass is needed from gravitational lensing in galaxy scale systems. This is problematic, because it can not be solved by neutrinos. But is this sample of galaxy systems isolated (really into the MOND regime)? (§4.5)

Chapter 5

Problems and successes of CDM

> "In the framework of general relativity, the standard model of cosmology (ΛCDM) provides a successful description of the Universe. In this model, the same fluctuations which give rise to the observed small variations in the temperature of the cosmic microwave background (CMB) grow under the force of gravity, and eventually form observed galaxies and other nonlinear structures such as filaments, voids, groups and clusters of galaxies [KP07]."

In the previous chapter MOND was scrutinized, and now we shall consider the problems and successes of dark matter theory, both individual and general. Descriptions of the major topics in dark matter theory are summarised (unless they are already brief) and put together in the evaluation report in the last section.

5.1 Dark matter candidates and detections

As discussed in Chapter 2, there are many thinkable candidates for dark matter particles although several candidates are already ruled out by observations. Due to the observed deuterium fraction in the Universe, we expect the dark matter to be non-baryonic, so not built up out of protons and neutrons as the ordinary matter around us. Also, direct detection experiments of the most probable candidates for baryonic matter, MACHOs, got negative results. We know that at least one non-baryonic dark matter particle exists: the neutrino. Experiments have shown that these particles have a (very tiny) mass, although these experiments can so far only give a lower and upper limit of this mass. On top of this, neutrinos are thought to be numerous. The problem is that they are too hot (which basically means they move too fast) to construct anything with. The dark matter halos that are needed around galaxies can never be built up from neutrinos. If neutrinos cluster at all, they are only expected to cluster at really large scales, like in clusters of galaxies.

Considering all this, the only realistic options left are particles that are both cold (moving slowly, or are heavy) and non-baryonic. These particles are not found within the Standard Model of particle physics, but can be created if this Standard Model is extended into supersymmetry models (SUSY). This requires also an extrapolation of known physics [GKT90], although it must be stressed that the original motivation for supersymmetry had nothing to do with the dark matter problem [KM02]. The dark matter particles just appeared in this theory.

As discussed before, there are many different dark matter particles which follow from SUSY, of which most are thought to be destroyed after the Big Bang. The lightest particle, the neutralino, is thought to be stable. This is currently the best dark matter candidate available. The particle is part of the Minimal Supersymmetric Standard Model (which basically means it will appear in all supersymmetric models) and it is not charged so it will not interact with other particles. Moreover the density of neutralinos that is expected is remarkably close to obtain the observed density of the Universe [KM02].

With these properties the neutralino is just somewhat more favoured by most scientists than another, heavier candidate for dark matter: the axion. Axions would also have been produced in the Big Bang. While these two particles are the most popular and dark matter searches concentrate on them, there are many more (exotic) particles follow from several physical models of the early Universe. As Lawrance Krauss puts it:

> "..Finally, of course, there are a host of unmotivated dark matter candidates that are being discussed, demonstrating once again that beauty, even in science, is in the eye of the beholder [Kra07]."

5.1.1 Dark matter detection?

So far particle physics experiments have not succeeded in detecting any of the dark matter candidates (apart of course from the neutrino). There was one claim for detection by a group from Italy and China, DAMA, who claimed they had measured more hits in their detector in June as in December [Bel01]. In the case that the Universe is filled with dark matter this is indeed expected, because in June the Earth's rotation velocity around the Sun is in the same direction as the Sun's motion through the halo. However, this result is really controversial, mainly because a group in the United States performed a similar test without any results [Abu00].

Although dark matter is not detected yet, many programs have started to search for it. In particular the expectation is that if dark matter indeed consists of neutralinos or axions it will be detected within a couple of decades.

5.1.2 Dark matter proof

With the exception of the hotly debated result from the DAMA group dark matter particles have never been detected directly. All dark matter proof is thus indirect. The most convincing proof for the existence of a non-baryonic dark matter component from an individual case, comes from a study of the so called "bullet cluster" of galaxies. The relevant paper from September 2006 was even called "A direct empirical proof of the existence of dark matter" [CBG06]. The bullet cluster system actually consists of two clusters that are currently in a merging process. Tracing both the stellar component and the plasma of the system through lensing showed that the dominant baryonic component centre of mass was really offset from the total mass centre of the system. According to the authors, this convincingly showed that the majority of the system is unseen *and* that the additional gravitational force can not be explained starting from the luminous mass with an alteration of the gravitational force law. The main results of the research are shown in Figure 5.1.

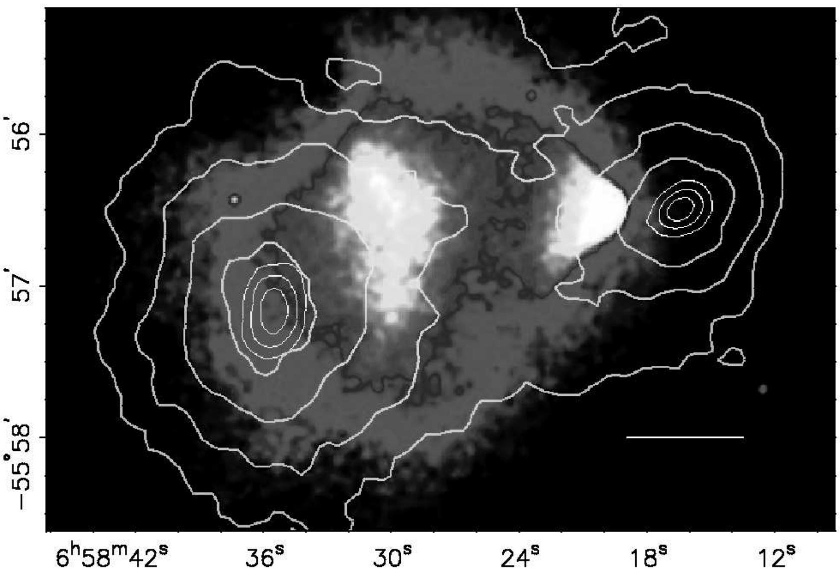

Figure 5.1: Shown in greyscale is the light emitted from the gas (the baryonic component). The white contours are measured from gravitational lensing and thus indicate all the mass in the cluster. You can see that the two components' centres are offset from each other [CBG06].

Sanders [San07a] points out (as was quoted in the previous chapter) that the bullet cluster doesn't provide an extra difficulty for MOND other than the proof that the unseen matter that MOND is still missing in clusters is non-dissipative. While this interesting result can be seen as a very convincing proof for dark matter, it does not immediately rule out its competitors. In particular MOND is not falsified, because most MOND supporters had already accepted at least one form of dark matter in clusters: heavy neutrinos.

While the bullet cluster observations shown in Figure 5.1 were perceived as a step forward for dark matter theory, Angus and McGaugh [AM07] claimed that the high impact velocities of the two clusters onto each other, form a problem within a CDM model. The observed velocity can only be modelled if certain hydrodynamical effects take place in the gas itself.

5.1.3 Dark matter candidates and detections – Conclusions

Dark matter is probably non-baryonic and cold, the most popular candidates are the neutralino and the axion. These particles, which have the right properties (mass, “coldness”, non-interacting, stable and overall density in the Universe) were already predicted by particle physics. This strengthens the theory. No detections have currently been made of these particles, however. Only once a positive test result was obtained, but it is heavily debated. If dark matter consists of neutralinos or axions it is expected to be detected within a couple of decades by new and improved detectors. The most direct dark matter proof is obtained from observations of a colliding pair of clusters: The Bullet cluster. Here it is shown that there is an unseen component, not what kind of dark matter it contains. Angus and McGaugh created an individual problem for dark matter theory, stating that the bullet cluster velocities are too high for a standard CDM Universe.

5.2 Cosmological models

> “Once you have fit the latest observations of the cosmic microwave background, you have basically determined all of the parameters in the model to an accuracy of 5 to 10%, and there’s no flexibility left to fit the astronomical data. Yet, remarkably, the model fits a host of observations.” (Joel Primack in [Sch07])

The great power of cold dark matter models is that they connect the smallest and the largest signatures that we know in the Universe. The smallest signatures being the imprint of the Universe 300.000 years after the Big Bang, the *Cosmic Microwave Background*, as it is shown in Figure 4.3. Cosmological models of CDM Universes predicted the amplitude and the spectrum of the tiny fluctuations in the cosmic microwave background [Hol89] as well as the distribution of galaxies that are thought eventually to grow out of these tiny initial fluctuations. These predictions could later be confirmed by observations [Spe06]. The model is remarkable successful on scales larger than a few megaparsecs [KP07] (about ten million light years).

Once a form of dark matter is chosen, full simulations of the Universe and the growth of structure can be made. These models do show the right amount and distribution of matter on larger scales (galaxies and clusters of galaxies). Because dark matter is not interacting much, it is relatively easy to model. Basically you only need the gravitational laws to put in. The extra gravitational pull of the dark matter makes sure that structures can grow out of the initial seed density fluctuations in the right timescales to form galaxies at the time we observe them. The baryonic part of this growth is however more complicated and it is often more challenging to put baryons, and all the complicated physical laws that come with them, into a cosmological simulation. A rather remarkable thing about pure CDM simulations, showing just simulated dark matter particles, is that they look very similar on very different scales. The dark matter halo of a cluster with its individual galaxies around it can not be distinguished from the model of an individual galaxy itself with small dwarf galaxies orbiting. This is illustrated in Figure 5.2. All the observational differences that we see today in systems if different sizes has thus to be due to the different laws applicable to the baryonic component on different scales. Also the diversity we observe between galaxies of the same size, like elliptical and disk galaxies has thus to be input of the baryons.

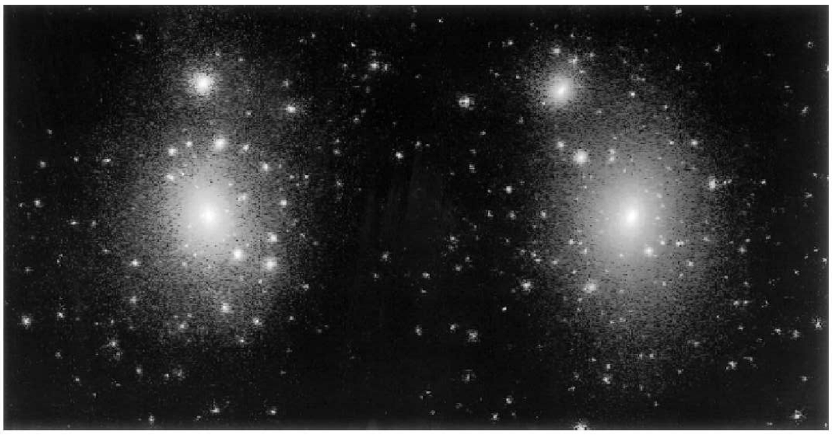

Figure 5.2: Two images from a CDM simulation. On the left a cluster of galaxies, on the right a galaxy with dwarf galaxies around it. Shown here are only the dark matter particles. Can you see the difference? (Credit: Ben Moore, image taken from his lecture notes at the Milky Way summer school in Heidelberg 2007)

5.2.1 CDM on galaxy scales

While the simulations, as stressed before, work well on a cluster of galaxies scale, on the galaxy scales there are some problems. Firstly, the number of small halos that we see around individual galaxies in the simulations outnumbers by far the dwarf galaxies around the galaxies we see today. This problem is known as the "Missing satellite problem". In general this problem is nowadays solved by assuming that the satellites are there, but that they have remained dark (no stars were formed) due to physical processes at the time they formed. Also, in the last couple of years more and more fainter dwarf galaxies are discovered, bridging the gap between the number of predicted and observed smaller systems. A second, maybe more problematic, issue is the shape of the halo that is expected from modelling. Theory predicts too much matter within the centre of the galaxies. This central density of dark matter, called the *cusp* is not observed [Gil07] and there are even results showing that, at least in some systems, it might not exist at all. An example here are the globular clusters of the Fornax dwarf galaxy, which we already encountered in the last chapter. If Fornax had a cusp of dark matter, as indicated by the theory, the system of orbiting globular clusters would have sunk to the centre by now. But also here results are coming up which show that actually the cusp may be somewhat shallower, especially in smaller systems [Ric04].

Angus et al. point out that while MOND is missing matter in clusters of galaxies, CDM predictions are still missing matter on the scale of ordinary galaxies. Their figure to show this is plotted as Figure 5.3.

> "But CDM suffers an analogous missing baryon problem in galaxies in addition to the usual dynamical mass discrepancy, yet this is not widely perceived to be problematic." [AM07]

5.2.2 Cosmological models – Conclusions

CDM models can connect the small scale (CMB radiation) and large scales distribution of structure in the Universe together almost perfectly. Both matches were first predicted and then observed. On the level of galaxies there are both missing satellites and missing mass. The first problem is generally thought to be solved by assuming that the missing satellites are still dark. The second problem, missing mass in the center (the cusp), might be more problematic.

5.3 Dwarf galaxies, Rotation curves & Gravitational lensing

CDM seems to be in general more in agreement and less in trouble with observational results of dwarf galaxies [KP07, LMP06] and with gravitational lens-

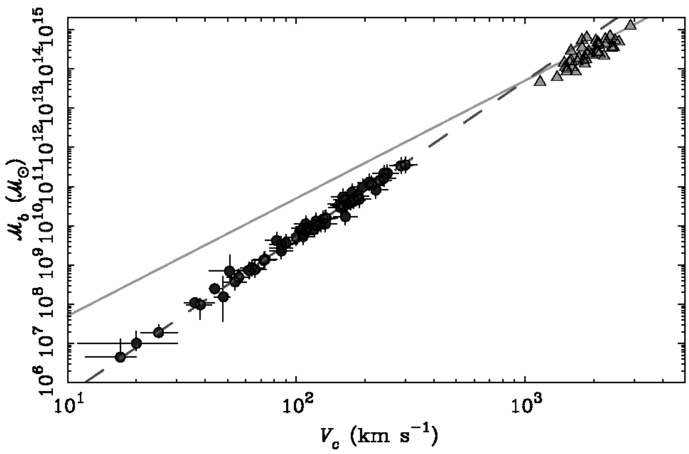

Figure 5.3: Figure of velocities versus baryonic mass of galaxies (circles) and clusters (triangles). The prediction of CDM models is overplotted as a solid line, MOND predictions are the dotted line. While MOND predicts too much mass in clusters, CDM is still missing mass in spiral galaxies. The vertical scale shown here is logarithmic, which means that with every step a power of 10 is added. (Figure from [AM07].)

ing both from clusters of galaxies as from galaxies alone [TC07, FSF07]. On the other hand, they have more trouble fitting the rotation curves of low surface brightness galaxies (LSB) as different observations require contradictory amounts of dark matter [MB98]. Another problem which was also discussed in more detail in the last chapter, is the dark matter content in tidal dwarf galaxies. According to dark matter theory no dark matter content is expected in tidal dwarf galaxies, because they recycle just the baryonic material out of the disks of the colliding galaxies. However, the observed rotation curves of a couple tidal dwarf galaxies do require extra dark matter mass [Bou07].

5.3.1 Dwarf galaxies & Gravitational lensing– Conclusions

Dwarf galaxy rotation curves are in general reasonably well fitted, but LSB galaxy rotation curves form a problem for CDM theory. Observations from gravitational lens observations support the theory. An individual problem is formed by the observations of the three tidal dwarfs. They were supposed to have no dark matter content yet are observed to contain some unseen mass.

5.4 Physical relations

Because luminous matter and dark matter are less coupled in CDM simulations, it is harder to couple the phenomenology of galaxies to their mass content. This was much more easily done in MOND which explains their ease with relations like the Tully-Fisher relation and the Freeman and Fish laws.

We also saw in the previous chapter that it is possible to make a physically motivated link between the three parameters of the fundamental plane in a MOND Universe. This is quite less obviously done in a dark matter paradigm, because with dark matter involved the linear relation between luminosity and mass is broken. Furthermore, it is harder to determine the effective radius, since dark matter is thought to spread out until large distances. Even if it is assumed that dark matter and ordinary matter are mixed in a constant ratio, this doesn't give a sufficient explanation, because the tilt of the fundamental plane is not accounted for. To explain this observed tilt is a major problem in astrophysics today, especially when the challenging population of low surface brightness galaxies is taken into account [Sca06].

5.4.1 Physical relations – Conclusions

Due to the broken relation between observed mass and the dynamics of the system as a whole, it is much harder to give a physically motivated basis for observed relations between the internal velocities and the shape and brightness of galaxies, both spiral and elliptical.

5.5 Evaluation Report

General Successes

- Dark matter particle candidates are a prediction from another field of science, particle physics, and are predicted to have the right properties (§5.1)
- Prediction and confirmation of spectrum density fluctuations (§5.2)
- Prediction and confirmation of the distribution of large scale matter over the Universe and the connection with the initial density fluctuations (§5.2)
- Far-fetched cosmological models (§5.2)
- Gravitational lensing observations (§5.3)
- Dwarf galaxy properties (§5.3)

General problems

- No direct detection DM particles (§5.1.1)
- Problem with density profile of galaxies: There seems to be no cusp (§5.2.1)
- Problems in explaining LSB galaxy rotation curves (§5.3)

Individual Successes

- Direct detection of a dark component in the bullet cluster (§5.1.2)

Individual Problems

- Dark matter needed in tidal dwarf galaxies, while this is not predicted from theory (§5.3)
- One model shows the velocities of the bullet cluster are too high for a CDM Universe (§5.1.2)
- The globular cluster system of Fornax (§5.2.1)

Predictions

- If dark matter is built up out of neutralinos or axions it will be detected within a couple of decades (§5.1.1)

Debated Matters

- Is dark matter already detected by DAMA? (§5.1.1)
- Missing satellite problem? (regarded solved by some) (§5.2)

Chapter 6

A Comparative Evaluation of the theories

In this chapter an evaluation will be given, concentrating purely on the empirical problems and successes discussed in the previous chapters. In the next chapter more attention will be given to social and aesthetic arguments and criteria supporting or criticising the theories.

6.1 Empirical Success

In the previous chapters empirical successes and problems for each of the two theories are reviewed and a evaluation report is presented on the several topics that were discussed. Both these empirical evaluations are summarized and put together in Table 6.1. This table gives an overview of the content of Chapters 4 and 5. While it can be clarifying to list and compare all arguments in such a way, this table can certainly not be seen as a final comparison between the truth value of the two theories. Firstly, because not all data is at hand yet to make a clear decision on all points. For instance, MOND cosmological models are part of a relatively new research area. Secondly, because it is impossible to show all the auxiliary hypotheses and complications within the theories in this table. For instance, the "missing satellite problem" is a problem for CDM theory. However when assuming certain physical conditions in the era when stars are formed it is possible that a lot of the theoretical expected satellites remain dark and therefore undetected. The question whether or not CDM is in agreement with the number of satellites observed is thus hard to answer. Comparable problems where encountered with many issues stated in this diagram, which have given a divided success score (A/D). Basically this score means they can be in agreement if some auxiliary hypotheses are used. A divided success score can also mean that there are some (minor or individual) problems on this issue, but that in general the theory agrees with the fact.

Question marks are used to mark issues that will need further future research to be solved.

Although simplified, from this table it is clear that while CDM has succeeded where MOND has failed at some points, there are also points where MOND is in agreement and CDM is not. Basically this means that the two theories are hard to compare on an empirical basis, called a case of *divided success*. Interestingly, if the table is used in a quantitative way by awarding 1 point for every success −1 for every problem, 0 for unresolved issues and $\frac{1}{2}$ points in between, both theories come to approximately the same end score. However, I don't want to advocate such a quantitative statement as I am convinced not all issues stated above should be given the same weights in the final consideration. For instance, is a full working cosmological model more or less impressive and/or fundamental than a fit to rotation curves? If one wants to make a clearcut distinction from this diagram regarding one or the other theory, these kind of choices have to be made about which observational or theoretical successes or failures are more important than others.

6.2 Testable predictions

Apart from the observational facts that the theories have or have not already explained, both theories have also made predictions. Based on the successes and problems discussed in the previous chapter, which theory has made the strongest predictions and will therefore be the easiest to falsify? For according to the vision of Karl Popper, the theory which makes the strongest predictions will be the better one (once these predictions can be verified experimentally).

Focussing on the indirect proof of dark matter, it is hard to make a real distinction, since the effects of dark matter gravity mimic the general effects of MOND and the other way around. Distinctions might be made through even more careful study of (LSB) galaxy rotation curves and in particular lensing effects with individual galaxies. MOND here makes a very strong prediction that individual galaxies should not contain much extra unseen mass. The dark matter paradigm would require unseen mass, since they need galaxies to have a dark matter halo. Lensing on galactic scales thus promises to be a strong test for both theories. The prediction for the exact shape of galaxy rotation curves is stronger in MOND, since they use less free parameters in the fitting process. A further option might be to look at a more cosmological scale at several predicted physical processes. While the cosmological modelling of MOND is still starting up, some predictions are already made. Observational processes that might make a distinction would be bar formation in galaxies, the merging rate of galaxies and the time in which mergers proceed.

Of course the most obvious and the only direct falsification of MOND would be the detection of a dark matter particle like the neutralino or the axion. As the creator of MOND, Mordehai Milgrom, states himself:

General observational facts	CDM	MOND
CMB radiation	A	?
Gravitational lensing	A	A/D
Dwarf galaxy properties	A	A/D
HSB rotation curves	A	A
LSB rotation curves	A/D	A
Number of dwarf satellites observed	A/D	?
Mass distribution in galaxies	D	A
Mass distribution in clusters	A	A/D
Tully Fisher relation	A/D	A
Fundamental plane	A/D	A
Direct detection	A/D	N
Merging timescales	?	?
Individual observational facts	**CDM**	**MOND**
Missing mass in tidal dwarf galaxies	D	A
Fornax globular cluster system	D	D
Rotation curve of the Draco dwarf galaxy	A	D
Velocity of the bullet cluster	D?	A
Theoretical Modelling	**CDM**	**MOND**
Full cosmological models	A	A/D
Structure growth and distribution	A	?
Predictions from particle physics	A	N

Table 6.1: Problems and successes put together of both CDM theory and MOND. Legend: A: agreement, D: disagreement, N: not relevant, A/D: in agreement but (yet) problematic, or in agreement if an auxiliary hypothesis is used. A question mark is put if further research is necessary.

> "If dark matter is detected, the question will be answered."
> (Milgrom in [Sch07])

If the neutralino or the axion really exists, the expectation is that it will be detected within 10 to 15 years from now [Sch07]. While a detection will clearly falsify MOND, a non-detection of one of the most popular dark matter particles in the coming 20 years will probably not falsify dark matter theory as a whole. There are so many dark matter candidates possible that a non-detection can always be explained in different properties of the "real" dark matter particle. It is to be expected that the theory will lose some of its main credibility however.

One additional way to test MOND is to investigate special places in our own solar system where the gravitational fields of the Sun and planets cancel each other out. The total gravitational field is low due to the cancellation and MOND effects should be observable. Although only a relatively low cost satellite could research these predictions, no founding money has been found yet for such a flight.

6.2.1 A future perspective

So far it seems that MOND is easier to falsify than dark matter theory and has made some strong predictions that can be researched. However, if the predictions are not proven correct, it is hard to foresee whether MOND researchers will really give up their theory, or if they would come up with auxiliary hypotheses to save the core of the theory. We have seen this happening before, when MOND scientists were forced to use massive neutrinos to complement their theory to match cluster observations. It seems to me that only the verification of the strongest CDM prediction: a detection of an unknown dark matter particle, could really falsify the idea on a short timescale. For CDM theory, the non-detection of dark matter particles in the next decades alone will probably not be enough to make scientists switch to alternative theories, because there are so many other dark matter particles possible. Maybe a large switch will be made if stronger evidence is accumulated for MOND. Although there are currently no large undertakings to research MOND itself, also a neutrino mass (which is to be measured by the KATRIN experiment) of around 2eV might make scientists change their mind. In the dark matter paradigm the mass of the neutrino is thought to be much less. Above this, the missing mass on cluster scales is perceived as one of the most serious problems for MOND which will then be solved.

Chapter 7

Non-empirical Arguments

We have summarised all empirical arguments in favour of and against both theories. But in Chapter 3 it was already shown that also non-empirical, for instance aesthetical, arguments can play a large role in scientific practice. The importance of such arguments was stressed by philosophers as Kuhn and Latour. To be able to discuss the influence of these aesthetic arguments on the debate between MOND and CDM theory, I will first discuss the classification of aesthetic arguments one by one as they were described by McAllister [McA96] for both theories. Subsequently, I will try to say something about the sociological factors within this discussion (another "ally" according to Latour), although I admit that is not possible to give an objective overview on this matter.

7.1 Aesthetic arguments

- Form of symmetry

  Through the complexity of the TeVeS theory it is too hard for me to judge whether the theory is more, or less symmetrically beautiful than general relativity on its own, which is usually regarded to be beautiful and symmetric. On first investigation, CDM theory seems to be more symmetric, simply because they expect more spherical symmetric gravitational fields due to the (almost) spherical dark matter halos, but also because the dark matter theory seems invariant under scale changes. Over a whole range of scales dark matter simulations look quite similar as was previously shown in Figure 5.2.

- Invocation of a model

  While it has never been suggested before on such a large scale, dark matter theory does show analogies with previous scientific findings. For instance within our solar system. By just following and holding on to gravitational laws, disturbances in the orbits of planets in our own solar system led scientists to believe there must be more bodies that were too faint to detect at that time. Indeed the mysterious planets were later discovered to be Neptune (through distortions in the orbit of Uranus) and Pluto (through distortions in the orbit of Neptune). Analogously, today many planets around other stars are discovered by tracing the effects of these planets on the stars they're orbiting. The hypothesis that unexplained features in orbits can be due to (yet) unseen masses has thus successfully been used before in scientific history, although never on such a scale (recalling that dark matter is thought to outweigh baryonic matter by several factors).

On the other hand, a similar analogy can be found for MOND. While scientists used to explain the peculiarities in the orbit of Mercury by assuming there was another, not visible, smaller planet which was causing them such a planet was never found. In hindsight it turned out that not the planets in the solar system, but the gravitational theory itself needed an update. Using Einstein's general relativity, of which Newtonian gravity theory is a special case, the orbit for Mercury could be perfectly explained.

Also, it is certainly not the first time that a law has been proposed that is based on empirical evidence only and not on an underlying theory. The empirical evidence in this case will be the rotation curves in galaxies which were the start of the theory and were used to shape it further, for instance to determine the value of a_0. One might see an analogy with the theory of Kepler of the rotation around the Sun as discussed in Chapter 3. Kepler didn't start from the then governing theories or metaphysical worldviews either, but just posited a law for the movement of planets based on observations of their orbits. This is certainly an analogy MOND scientists will like, since the Kepler law is used as an example for a revolutionary theory that changed the metaphysical thinking of that time. There are however also differences between the scientific process for Kepler's law and MOND. Dark matter theory is for instance also much more based on empirical evidence than the theory that planets move in purely circular orbits ever was.

- Visualizability/abstractness

  While both theories are hard to visualize, also here the dark matter theory seems to have a slight advantage. I noticed while writing this thesis that it was easier for me to imagine some dark matter content with the same gravitational laws, than a gravitational law that suddenly starts to change. While this might be a manifestation of my greater familiarity beforehand of dark matter theory, I also noticed this problem in the papers on MOND simulations. Before the simulations are really performed it is often hard to predict how certain processes will change or whether a certain physical process will speed up or slow down. For example, at first some scientists speculated that the merger process of large galaxies would speed up using MOND laws, after carefully performing simulations they found out that it actually does slow down. Unexpected behaviour like this shows that it is tricky to "hold the whole theory in your head" that is to visualize the process and be able to tell how it will perform from that visualized mind experiment.

Even worse to visualise are the three separate fields needed in the TeVeS theory underlying MOND. General relativity, just one field, is already hard to visualize, although during the years there has been a very popular image of seeing the gravitational field like a sheet that can bend due to heavy objects (see Figure 7.1). Such an image has not been constructed for TeVeS yet and the question is whether this is even possible or if this combination of three fields is too complicated to be visualized by the human brain.

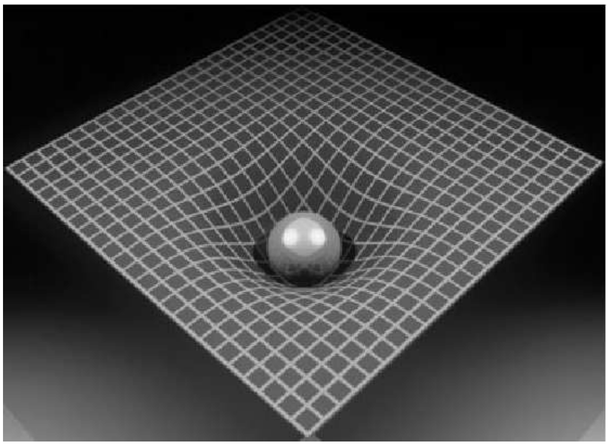

Figure 7.1: A visualisation of a massive object which is curving spacetime in general relativity. (Figure from [Hog07])

- Metaphysical allegiance

  One of the problems of MOND is that it stands alone as a theory, it is even lacking a full theoretical background itself. Dark matter theory connects a lot of theories together, not only with particle physics theories which predicts the particles needed. CDM also forms a steady metaphysical framework together with dark energy and inflation theory (a mathematical theory that described the very first split-second after the big bang) in the so-called "Concordance model". The weird cold dark matter particles that can be felt, but not seen, seem to fit in nicely with the whole picture of the mysterious, almost alienating Universe in which all the stuff we "know" (the baryonic matter) plays only a very marginal role. Subsequently, to implement mysterious particles hardly feels problematic in a Universe which is dominated by hardly understandable quantities like black holes and quasars anyway. Although the discovery of laws and theories by empirical data is not new, MOND does not connect with any existent theories. Even worse, because it needs its own TeVeS theory it dismisses the beloved general relativity theory in its present form.

- Form of simplicity

  Both theories are better described as being complex rather than simple. While some people will regard it as being more simple to just "put some dark matter in the places where you empirically need it", MOND is the theory that used to have a reputation of simplicity. With one simple ad-hoc hypothesis about gravitational forces it can, for instance, explain many complex features in the rotation curves of galaxies. Dark matter theory, on the other hand it has a more complex image, in particular because the theory makes connections between rather mysterious theoretical theories like initial density fluctuations, dark energy and inflation theory.

  While thus in origin MOND had a head start considering the simplicity criterion, MOND has somewhat lost the attractiveness of the simplest theory over the past decades. One of the reasons for this is that TeVeS theory introduces three different fields in spacetime, a tensor, vector and scalar field, which is more complicated than the rivaling one gravitational field used in general relativity. Many physicists feel uncomfortable with this complexity. As cosmologist Joel Primack puts it:

  > "Bekenstein's paper is monumentally complex and ugly. (...) If other cosmologists want to waste time on it, that's great, it means less competition for me." (Joel Primack in [Sch07]).

  Another reason MOND has lost its initial air of simplicity to some scientists is because it is forced to use some form of dark matter: massive neutrinos. While, as discussed in the previous chapter, this is not necessarily a bad development for the empirical content of the theory, it does take away some of the aesthetic beauty of the initial MOND law which used to explain problematic observations without taking any form of dark matter into account.

  On the other hand, also dark matter theory has problems. Pointing to the velocities within the Bullet Cluster that can not be explained in a standard CDM Universe, Sanders claims:

> "MOND needs some dark matter, but that could be in the form of neutrinos, which we know to exist. But apparently, the concordance model not only needs mysterious dark matter, but also additional new physics. This makes you wonder what is worse." (Sanders in [Sch07])

7.2 Sociological arguments

This kind of argument is really difficult to pin down, because no research has been conducted on how many scientists are in favour of either one of the theories and how they feel about the other theory. However, it is clear that from the amount of scientists that favour the theory, MOND will be the theory with the least "allies" on this account. From MOND scientists it is often heard that they feel their theory is not taken seriously enough by the rest of the scientific community. It seems to them that other astronomers are so embedded within the CDM theory they won't give any other idea a chance. The quotes below illustrate how some of the most profound MOND scientists feel about the attitude of the rest of the scientific community toward MOND.

> "There's certainly a sociological effect involved" (Bob Sanders in [Sch07])

> "I often run into an irrational wall that sometimes has an almost religious feel to it. When I ask people what proof I could offer to convince them, they often say "none". (...) There is a huge funding bias against MOND." (Stacy McGaugh in [Sch07])

However, there are also scientists who do not believe in any sociological effect and rather think that MOND would be taken seriously by more scientists, if only it would be more successful:

> "If they came up with a relativistic version of the theory that fits cosmic-microwave-background data, large-scale-structure data, gravitational-lensing data, and matches the solar system tests of relativity, I would be very interested in exploring the theory. And if this new theory made predictions that were confirmed by experiment and contradicted the [concordance] model, it would be widely accepted by the scientific community."(David Spergel in [Sch07])

Chapter 8

Discussion and Conclusions

In this thesis an overview of both empirical and non-empirical arguments are given both in favour of and against the two most successful theories that try to explain rotation curves of galaxies and galaxy velocities inside clusters. While the most popular theory explains the discrepancies by assuming there is a large unseen mass around each galaxy and cluster, the second theory investigated here assumes that the discrepancies are caused by different behaviour of the gravitational laws in low gravitational fields. We put both these theories, (Cold) Dark Matter (CDM) and Modified Newtonian Dynamics (MOND), to the philosophical hypothetico-deductive comparative test. Hypothetico-deductive (HD) testing was originally designed by Hempel and Popper, but first explicated for theory comparison purposes by Kuipers [Kui00]. This thesis provides an example of the use of this comparitive evaluation method in scientific practise. HD evaluation is used to discover whether there exists a theory that is the better one regarding the empirical facts it can or can not explain. Furthermore, also non-empirical arguments, aesthetic arguments as classified by McAllister [McA96] and sociological arguments, are researched.

Empirical arguments

The empirical arguments are summarised in Table 6.1. While this result is very much simplified and does no justice to all details of both theories as discussed in Chapters 4 and 5, the table clearly shows that the theories reveal mixed success. Where MOND theory is slightly more successful on a scale of a galaxy, CDM theory has been correctly predicting the small scale fluctuations and the large scale distribution of matter inside the Universe. Also CDM theory is ahead in cosmological modelling, which just became possible for MOND now it has found a connection with general relativity through the Scalar-Tensor-Vector theory (TeVeS), a theory which itself has problems because of its complexity and bottom-up character. On the other hand MOND has a major advance in predicting rotation curves of galaxies. Another achievement of MOND is that it physically correlates the appearance of a galaxy with its internal dynamics. In MOND the observed matter really is all there is, on galaxy scales, and therefore uniquely defines the gravitational field and the internal motions. With this link, previous observed physical relations in galaxies between luminosity and velocities of galaxies get a more physical background. However, MOND seems to have more problems than CDM with gravitational lensing observations and the individual rotation curves of some dwarf galaxies.

In this thesis we have regarded both CDM and MOND mainly as theories at this particular moment in time, while in fact they might also be described as (the core of) different research programs, because of all they encompass. If MOND ever becomes the dominant theory this will really induce a paradigm (or research program) shift.

The question if both theories, or programs, are degenerating or progressing (in Lakatos' terminology) can be answered on different levels (as was already discussed in Chapter 3). A direct comparison of the two theories within a snapshot in time, pursued in this thesis, is answered by the divided success score in their evaluation. In fact we have compared the two research programs by terms of their best (current) theories. Compared to each other neither CDM theory nor MOND satisfy the three conditions set by Lakatos. Although both of them have some content not possessed by the rivaling theory, they do not explain the successes of each other and neither one of them has evidently more corroboration.

We could also have pursued a comparison of the research programs themselves and how they deal internally with their anomalies, as suggested by the philosophy of science of Lakatos. Both research programs, MOND and CDM, have shown in the past that they will defend their hard core if any anomalies show up (negative heuristics). We have also seen that it is possible to talk about these programs in terms of positive heuristics as well, which is their strategy to defend their main core. Dark matter theory, for instance, has a lot of physically different dark matter particles to choose from to find the one that best fits their needs. Although an evaluation of the research programs themselves in terms of their progressive or degenerative spirit would be a very interesting subject for further research, a full symmetric comparison of programs seems not feasible at this point, because both programs are not at the same stage of their development. Especially MOND is still in the stage of connecting their phenomenological approach to a solid underlying cosmological theory. It will need some more time to establish its explanatory power and positive heuristics as a research program. Until then, they will probably coexist.

Although the current uncertainty of having two theories and the (sometimes fierce) competition can be a nuisance to scientists, the coexistence of both theories is in the best interest of science in general. Until one of both theories can give a definitive answer to the success questions the challenges they provide for eachother will improve both programs. Even if a cold dark matter particle is found in the near future still CDM theory will be facing the challenge to explain why rotation curves trace the luminous component so accurately and what the basis is for the observed physical relations for galaxies. This interaction by competition creates a very healthy scientific environment in which theories are forced to face and solve their anomalies.

Aesthetic arguments

When going through the list of aesthetic arguments as classified by McAllister it is prominent that most aesthetic arguments can be argued to be in favour of Cold Dark Matter theory. The theory seems to have more "allies" here, also apart from the larger number of astronomers supporting the theory. Cold Dark Matter theory connects better to other theories and seems to fit better in the existing world view of our Universe. It also is easier to visualize and shows more symmetry. While MOND had the advantage of being more simplistic to some standards, it has lost this advantage at least partly through the acceptance of at least one dark matter particle (the neutrino) and because its underlying theory, TeVeS, is more complex. On the other hand, also CDM theory has its problems with simplicity.

Is there a better theory?

From an evaluation of purely empirical arguments at this point in time none of the theories can be called the "better theory". The only motivation for calling one theory better than the other would be to argue that several topics from the list presented in Table 6.1 are more important or more fundamental. Such a determination of a better theory is clearly subjective and outside the scope of this thesis.

It is remarkable that CDM theory performs so much better on the non-empirical criteria. Obviously this theory connects better to our current world view and has a lot of properties that we could seek in a beautiful theory. This does not entail at all that CDM is in the end a better theory. As described in McAllisters book, aesthetic criteria do change with time. It is possible that after some time we realise our current set of aesthetic criteria is not working for us any more to pick out true, or close to the truth, theories. In such a revolutionary period aesthetic criteria can shift. While it does not state that CDM is a better theory, the discussion of aesthetic criteria in Chapter 7 can perhaps explain why CDM is the much more popular theory. Not only did CDM theory develop first, it also connects better to our feel what a good theory should do for us.

Is it possible to combine these theories?

In such a case of divided empirical success between two theories it is important to raise the question whether the two theories might be combined in such a way that they complement each other. The new combined theory should, in the ideal case, include the successes of both separate theories and not their problems. In this way, the two theories could be moving away from interaction by competition into interaction by cooperation.

Due to their very different starting points, it seems not possible to fully reconcile the two theories. Although some scientists (including me) think, or hope, an even more fundamental theory, perhaps starting from an entirely different idea and forming its own resarch program, might be found that can connect both successful theories. In principle MOND and CDM are promising theories for such an approach, because their successes lie in such different domains. It is imaginable there would exist a theory which possesses both the large scale successes of CDM and the phenomenological, smaller scale successes of MOND. Perhaps this would take even another approach to gravity, a more fundamental general relativity theory.

Another approach is to try to implement the most successful part of the one theory into the other theory, by changing the theory such that the same effect is accomplished. For MOND partly this undertaking already started with the inclusion of massive neutrinos in their theory. By including this form of dark matter, they were able to solve their major problems on cluster scales. However the solution needed a heavier neutrino than predicted from CDM cosmology and is not applicable to any of MONDs problems on galaxy scales or smaller. Also it is not clear if MOND will be able to perform as well as CDM theory in simulations fitting the cosmic microwave background and the distribution of matter in the Universe.

Another way to bring the two theories closer is to try to let CDM theory look more like MOND on a galaxy scale, which is in current CDM theory the most problematic scale. To do so, the dark matter content in galaxies should be stronger linked to the visible content. For the greatest successes of MOND are the prediction of individual features in rotation curves and the physical motivation for physical relations. As all these successes are derived from the fact that the gravitational potential is fully determined by the visible matter, a way to introduce these successes into CDM would be to make a strong connection between the distribution of the visible and invisible (dark) matter content. How to physically motivate such a connection is still unclear however.

Conclusions

Researched in this thesis are two competing theories in astronomy: (Cold) Dark Matter theory (CDM) and Modified Newtonian Dynamics (MOND).

CDM is a very popular theory which explains certain observed problems by stating that a large part of the Universe exists of non-interacting, non-baryonic matter. MOND, on the other hand, prefers to solve the same observations by changing the Newtonian laws of gravity in certain regimes. This theory is far less popular among astronomers. A hypothetico-deductive evaluation of their empirical successes and problems shows that both theories are in a state of divided success. While MOND is slightly more successful on galaxy scales, it has additional problems on other scales. From an evaluation of aesthetic criteria, as classified by McAllister [McA96], we find however that CDM theory is much more appealing. This, together with its longer history and more solid cosmological theory, might explain the higher popularity of this theory, although it doesn't imply that CDM is in the end "the better theory". A different approach would be to try to reconcile the successes of both theories. Although their starting points are very different, the two theories show successes on almost complementary domains, which might justify such an approach. This could either mean putting dark matter on large scales into MOND and finding a solid cosmological background for it, or adjusting CDM such that dark matter traces the visible matter better on small scales. Or maybe in the end an entirely new research program will be needed to combine these two very successful theories.

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