CHAPTER I
Introduction to dark matter

During the last decades, evidence has constantly grown stronger that the mass fraction of the baryonic matter might have only a minor contribution to the total mass that is found in the universe. In fact it is argued today that up to 95 % of the mass in the universe eludes the eyes of the observers. Considering this large overabundance of dark matter, we still know very little about its nature and its distribution on large and small scales.

For the last few years the Cold Dark Matter (CDM) model has been used fairly successfully in explaining the large scale structure formation in the universe. However, on the scale of galaxies, the theoretical predictions of dark halo shapes disagree with observational evidence. Several alternatives have been proposed to fix the shortcomings of the CDM scenario, but there is no widely agreed on solution available yet. In spite of the dispute about the nature of the dark matter, there is plenty of evidence that can be considered as good proof of its presence. This introduction provides some overview on the current understanding of dark matter related issues. It is not intended to serve as an exhaustive review, but rather to highlight the fundamental ideas on which present research of dark matter is based.

1.1. Evidence for dark matter in the universe

1.1.1. Galaxy clusters

The first finding indicating evidence for a considerable amount of dark matter in the universe is credited to F. Zwicky (1937) who estimated the virial mass of the Coma cluster of galaxies from the peculiar motions of the cluster's members and compared it to the visible mass estimate. This method is still valid today, but bears large uncertainties from small number statistics, unvirialized systems, and kinematically unrelated interloper galaxies. Modern analyses (Carlberg et al. 1996) determined cluster mass-to-light ratios (M/L, always in solar units) to $\sim 300\ \mathrm{M}_\odot/\mathrm{L}_\odot$.

Another method of estimating the mass in galaxy clusters is by their X-ray luminosity. Most of the intra-cluster gas is diffuse, ionized and very hot, especially in dense and massive clusters. In fact, the temperature of the gas correlates with the velocity dispersion of the cluster's member galaxies and allows for an alternative probe of the gravitational potential of clusters (see Sarazin 1988 for a review). Assuming the gas in a hydrostatic equilibrium

– which might be a good approximation in some cases – the potential and thus the total gravitating mass of the cluster might be derived from the radial brightness profile. This has been done for several galaxy clusters; e.g., the Virgo cluster (Schindler et al. 1999), the Fornax cluster (Jones et al. 1997), and several Abell clusters (David et al. 1995; Cirimele et al. 1997). These studies conclude that the cluster systems are widely dominated by dark matter with typical values of M/L = 100 – 150, reaching as high as M/L $\approx$ 500 (Schindler et al. 1999).

1.1.2. Lensing

Gravitational lensing provides a fairly unbiased method of gauging the gravitating mass in the universe. It gives us the chance to probe the present galaxy and cluster mass profiles independent of the dynamic state of the systems. A very indicative example is strong lensing in galaxy clusters. There are several known examples, where giant lensed arcs in clusters are observed and may be used to trace the cluster's gravitational potential; e.g., Abell 2218 (Kneib et al. 1995; Cannon et al. 1999), CL 0024+1654 (Shapiro et al. 2000). In most cases the mass estimates derived from X-ray luminosities and gravitational lensing tend to disagree slightly. The lensing studies generally find cuspy matter distributions, coinciding often with the central cD galaxy of the lensing system. The inferred matter profiles of these clusters agree fairly well with the assumptions of CDM and demonstrate clearly the need for large amounts of dark matter within galaxy cluster systems.

In recent years weak lensing has turned out to provide a powerful tool to probe the dark matter distribution on large scales. The idea of weak lensing is that the underlying mass distribution exerts a weak cosmic structural shear on the galaxies in the line of sight. From this shear a two dimensional map of the total mass can be reconstructed (see Mellier 1999 for a review). This method profits from modern, more sophisticated numerical techniques as well as from new generation wide field imaging instruments. There have been weak lensing studies of galaxy clusters and superclusters (e.g., Squires et al. 1996; Gray et al. 2001) and of blank fields (e.g., Bacon et al. 2000; Wilson et al. 2001). Besides high values for M/L in the cluster regions, weak lensing results show that M/L in the intercluster space might also be high. Since for some studies the density of early type galaxies seems to coincide fairly well with the highest concentrations in the mass maps from weak lensing, it is argued that M/L for early-type galaxies may be universal. If this is the case the early-type M/L_B lies in the range of 150 to 300 $M_\odot/L_\odot$ and a range for Ω_m of 0.2 to 0.3 is favored.

1.1.3. Halos of galaxies

Additional evidence for the need of dark matter comes from the analysis of galactic rotation curves. Rotation curves of spiral galaxies have been explored for over forty years, beginning with the pioneering works of V. Rubin and W. Roberts. The fact that the rotation curves stay flat out to great radii argues for a large amount of dark matter in an unseen halo that surrounds the visible part of the galaxy. It turns out that the dynamical mass of the galaxy is largely dominated by the non-baryonic dark matter in the halo. The inferred total M/L is typically in the range of 10 to 50 $M_\odot/L_\odot$, depending on the class of the galactic system. While huge high surface brightness spirals supposedly sit in the centers of massive halos, low surface brightness and dwarf galaxies are especially dominated by dark matter on all scales. Elliptical galaxies, considered to account for most of the visible mass in the universe today, reside most probably also in giant dark matter halos (Griffiths et al. 1996; Rix et al. 1997, Loewenstein & White 1999). However, since stars in elliptical systems do not exhibit well ordered kinematics like that found in disks, testing for a dark matter halo requires different techniques. Results were achieved by the kinematics of gravitationally bound objects (e.g., globular clusters, planetary nebulae), the velocity dispersion from spectral analysis, and lensing. Thus, also for ellipticals the total M/L is rather large and in the range of 20 to 100.

The dark matter distribution in the central parts of galaxies is an issue with no widely agreed on solution. It is this part of the dark matter problem, which I address in this thesis. The challenges of separating out the different mass contributions and the implications for disk kinematics issues will be the focus of the following chapters.

1.1.4. Cosmological implications and the baryon fraction

The average density of baryonic and non-baryonic matter in the universe ρ_m is typically referred to in terms of the density parameter, Ω_m, which is defined as the ratio of the present ρ_m to the critical density $\rho_c = 3H_0^2/8\pi G$, where H_0 is the Hubble constant and G is the gravitational constant. Additionally, a cosmological constant Λ can be formally identified with the vacuum mass density ρ_v to account for "dark energy" in the universe that contributes to the final mass budget. A corresponding density parameter $\Omega_\Lambda = \rho_v/\rho_c$ can be defined. The total average mass-energy density in the universe Ω is the sum: $\Omega = \Omega_m + \Omega_\Lambda$.

In recent years there has been progress in constraining the possible range for Ω. Especially the very recent BOOMERANG and MAXIMA balloon experiments allow to probe the fine structure of the cosmic microwave background (CMB) to determine various cosmological parameters from the CMB anisotropies. These studies yield strong evidence for a flat universe with $\Omega \approx 1$ (de Bernardis et al. 2000; Stompor et al. 2001). These findings are in good agreement with the results from the Supernova Cosmology Project (Perlmutter et al. 1999). There is strong evidence for an accelerating universe and hence $\Omega_\Lambda > 0$. For an $\Omega = 1$ universe these results, including estimates from galaxy cluster analyses, yield a best fit of $\Omega_m \approx 0.3$ and $\Omega_\Lambda \approx 0.7$ to the data. Ω_m was defined to include both normal matter and dark matter, $\Omega_m = \Omega_B + \Omega_{DM}$. From M/L estimates it is already clear that Ω_{DM} comprises a large fraction of the total mass density. Another constraint for the baryonic mass fraction ρ_B comes from studies of primordial nucleosynthesis. The relative abundances of the light elements, especially deuterium, which was produced shortly after the Big Bang, can be used to confine the total baryonic mass content in the universe. In a recent review article, Tytler et al. (2000) conclude from a variety measurements of the deuterium to hydrogen abundance ratio that the derived value for $\Omega_B h^2 = 0.019 \pm 0.0024$, which with a Hubble constant of $75\,\mathrm{km\,s^{-1}\,kpc^{-1}}$ yields $\Omega_B \approx 0.036$. This value is in very good agreement with other estimates for Ω_B from Lyman-α forest absorption within the intergalactic medium and from galaxy clusters by means of their X-ray luminosity or the Sunyaev-Zel'dovich effect (see Tytler et al. 2000 and references therein).

In order to account for $\Omega_m \approx 0.3$ dark matter must be 5 to 10 times more abundant in the universe than the kind of matter that we know and that is made up mostly from baryons. Furthermore, perhaps less than half of the baryonic material is visible to the eye in the form of stars, gas and dust.

1.2. The nature of dark matter

We now know fairly well the amount of dark matter in the universe and how it is distributed on large scales. However, the nature and the physics of this elusive mass component remains very much unknown. As it has become evident, the missing amount of matter in the present universe cannot be explained by a single, hitherto undetected matter component. The matter budget is a multi-piece puzzle that is just being sorted out now.

1.2.1. Baryonic dark matter

Primordial nucleosynthesis can be used to convincingly predict the baryon fraction in the universe. A comparison of these predictions with presently observed baryons in the luminous components of galaxies and in the intergalactic medium shows that the observed baryons account for only about half of the existing baryons (Cen & Ostriker 1999). Interestingly, results from Lyman-α forest absorption studies find that the baryon budget seems to agree with nucleosynthesis expectations at $z \sim 3$ (Fukugita, Hogan & Peebles 1998). Apparently, a considerable fraction of the baryons must have eluded the processes of structure and star formation and remains hidden to the observers.

The stellar contribution of the baryonic matter ranges only at $\sim 10\,\%$ (Valageas, Silk, & Schaeffer 2001). Most of the present baryons are stored in the form of gas, mainly in galaxies and galaxy groups. The amount of baryons in these various gas components – fully ionized gas, diffuse, warm intergalactic medium, nearby Lyman-α absorption clouds, or cold diffuse of clumpy H_2 gas – is very difficult to assess. About 75 % of the baryonic matter is very likely to be composed of gas and stars, leaving about 25 % of the baryonic mass unaccounted.

The majority of these missing dark baryons can presumably be found in the halos of galaxies. These dark matter candidates are collectively called 'MAssive Compact Halo Objects' (MACHOs). There are extensive monitoring projects of stars in the Magellanic Clouds to look for microlensing events caused by the passage of a MACHO close to the line-of-sight (MACHO (Alcock et al. 2000), EROS (Lasserre et al. 2000), OGLE (Udalski et al. 1992)). These surveys showed that the Milky Way halo cannot be made entirely of MACHOs; at most, MACHOs contribute $\sim 20\,\%$ to the halo mass (Alcock & The MACHO-collaboration 2000; Lasserre & The EROS-collaboration 2000). However, if the MACHOs are as numerous as this upper limit allows, they could eventually make up for most of the missing dark baryonic component. If so, there would be twice as much mass in MACHOs than there is in stars.

On the other hand, the microlensing surveys constrain the average mass of halo objects to a range of 0.1 – 1 $M_\odot$. Building up the halo from such low-mass objects requires relatively high MACHO numbers. However, for an abundant mass component it is difficult to come up with a suitable formation process. The only dark objects known that have masses in the required range are old white dwarfs. Asteroid sized rocks are too small to cause the mircolensing events by their low gravity, while brown dwarfs and K-dwarfs seem to comprise only $\sim 1\,\%$ of the galactic halo mass. Despite the detection of white dwarfs in the HDF and proper motion surveys (Ibata et al. 1999, 2000), metal enrichment and infrared background considerations lead to the conclusion that white dwarfs cannot be sufficiently abundant to contribute significantly to the baryonic dark matter component (Fields, Freese, & Graff 2000). Thus, there is no consistent explanation for what a MACHO is and how the microlensing events can be satisfyingly explained. Alternative explanations are also being explored, like a LMC thick disk or halo star clumps. In such a case the cosmological relevance would be less.

There are more exotic dark matter types of baryonic origin being discussed, such as primordial black holes, which might be able to explain microlensing events. Primordial black holes might date back from radiation dominated stages of the universe and originate from the gravitational collapse of horizon-size energy density fluctuations (Jedamzik 2001). Yet, these objects have not been observationally confirmed and there is not much known about their quantity or their mass function.

1.2.2. Non-baryonic dark matter

Although the baryonic dark matter seems to be close to completely sampled, there is still a huge amount of missing mass to match the $\Omega_m \approx 0.3$ requirement. This component is referred to as non-baryonic dark matter. Likely, there is not only a single particle type that accounts for all the missing mass, but rather a variety of particles of varying significance (Sellwood 2000).

In the early 1980's neutrinos emerged as very attractive dark matter candidates. They are the only dark matter candidates known to exist. Although being massless in the standard model for particle physics, there has been recent evidence that neutrinos actually carry mass, which relies on the observational fact of neutrino oscillations. New Superkamiokande measurements allowed to estimate the $\mu - \tau$ neutrino mass-square difference to a few meV^2, attributing only tiny masses to the neutrinos themselves (see Caldwell 1999, and references therein). The small masses of neutrinos make it highly unlikely for neutrinos to represent the bulk of non-baryonic dark matter. Furthermore neutrinos belong to the hot dark matter type, being still relativistic when decoupling from the radiation field in the early universe. A universe dominated by a hot dark matter scenario does not agree with current galaxy evolution theories. These findings lead to the fall of the neutrino as the top dark matter candidate (for a review, see Primack & Gross 2001).

According to current theories most of the dark matter particles are rather massive and, as the universe became matter-dominant, they would have cooled to non-relativistic temperatures: this is cold dark matter (CDM). Particle physicists have assembled a vast zoo of possible CDM candidates, where most of them can be characterized as "Weakly Interacting Massive Particles" (WIMPs). Besides the initial requirement that WIMPs are massive and the postulation that they are susceptible to weak interactions they might also carry color charges. The stringent requirement is that they don't carry electrical charge. The strength with which the WIMPs interact with ordinary matter might span a wide range. The most physically motivated candidates for non-baryonic WIMP dark matter include neutralinos and axions (Kamionkowski 1998).

The neutralino is perhaps the best candidate for a WIMP. It is a neutral Majorana particle[1] and it is the lightest stable particle in the theory of supersymmetry (SUSY). It couples to ordinary matter with a weak-interaction strength, which might be in the sensitivity range of present-day high energy particle detectors (for a review, see Jungman 1996). Since it is

[1] A Majorana particle is equal to its own anti-particle.

stable, the neutralino itself is not supposed to interact via strong interactions or it would bind in nuclei and become observable in exotic heavy isotopes.

Another very good candidate for non-baryonic dark matter is the axion and its fermionic partner, the axino. They were introduced by particle physicists to solve the strong CP-violation problem in quantum chromo-dynamics (Peccei & Quinn 1977). In contrast to other CDM particles, the axion is relatively light, but symmetry breaking occurs at high energy scales; Hence early in the universe, existing axions could have cooled to become non-relativistic CDM.

There are several more highly exotic particles that might account for non-baryonic material, but the two kinds mentioned above, the neutralino and the axion, have the best chance for experimental verification. In fact, there have already been measurements of annual modulations in particle fluxes claimed as possible WIMP signatures in particle physics experiments (Bernabei & The DAMA Collaboration 1999), but the findings are very controversial and are still waiting verification of falsification by other experiments probing the same energy range. Eventually there are high hopes of finding SUSY particles with the Large Hadron Collider at CERN which is currently being constructed.

Until non-baryonic dark matter can be confirmed by particle experiments, it is worthwile to look at the spatial distribution of dark matter in the universe. A quite successful cosmological evolution model uses the ΛCDM scenario, which assumes cold dark matter and a non-zero cosmological constant. These models successfully recover cosmic large scale structure (e.g., Pearce et al. 2001), while high resolution simulations find strong subclustering and central dark matter cusps in galaxies (Fukushige & Makino 1997; Moore et al. 1999a). Since in observed galaxies evidence for these density cusps is very poor and there is no evidence for strong dark matter subclustering, modifications to WIMP properties are applied to solve for these shortcomings. Tests were made for self-interacting (Yoshida et al. 2000; Meneghetti et al. 2001) or fluid-like particles (Peebles 2000). Also warm dark matter has been proposed (Avila-Reese et al. 2001). However, all these modifications do not improve the situation satisfyingly; more questions arise and more options need to be checked. Of immediate need certainly is to constrain the dark matter distribution in galaxies more precisely before firm constraints can be issued regarding the nature and the interaction cross-sections of non-baryonic dark matter particles. Eventually, this thesis might contribute here a small piece to the solution of the grand puzzle.

1.2.3. MOND – A universe without dark matter

Although modern cosmology tends to adopt the idea of dark matter to account for discrepancies in the mass balance of the universe there is also a well elaborated approach explaining these discrepancies by a slightly modified gravitational acceleration. This concept called "MOdified Newton Dynamics" (MOND) was introduced by M. Milgrom (1983). MOND can be interpreted as either a modification of gravity through a change to the Poisson equation, or as a modification of inertia through a breaking of the equivalence of inertial and gravitational mass. MOND is implemented as a non-relativistic modification to the standard Newtonian gravitational acceleration field $\mathbf{g}_N$. The relation between the $\mathbf{g}$ in MOND and $\mathbf{g}_N$ is given by: $\mathbf{g}\mu(|\mathrm{g}|/a_0) = \mathbf{g}_N$, where a_0 is a new physical parameter with units of acceleration, and $\mu(x)$ is some function that asymptotically converges to $\mu(x) = x$

when $x \ll 1$ and $\mu(x) = 1$ when $x \gg 1$ ($x = \mathrm{g}/a_0$). For very low accelerations MOND predicts $\mathrm{g} = \sqrt{\mathrm{g}_N a_0}$. Apparently a_0 – which is of order $10^{-10}\,\mathrm{m\,s^{-2}}$ – scales with cH_0 to within a factor of 5 or 6. This ad hoc assumption has two immediate consequences for the dynamics in galaxies: (1.) The rotation curve for any galaxy becomes asymptotically flat and (2.) the asymptotic rotation velocity v_∞ depends only on the galaxy's total mass M as $v_\infty^4 = MGa_0$.

The implications of MOND are rather extensive. It solves not only the problems it was designed to solve, i.e., the explanation of galactic rotation curves without dark matter, but can be applied to a variety of problems. MOND seems to explain the dynamics of high and low surface brightness galaxies with reasonable values for M/L. Moreover, MOND satisfies the Tully-Fisher relation for spirals (McGaugh & de Blok 1998) and the fundamental plane for ellipticals (Sanders 2001). MOND also reproduces the actual velocity dispersions in all kinds of galaxy groups and clusters (Milgrom 1998). Furthermore the theory can also be used to explain the recently observed angular power spectrum of the CMB from the BOOMERANG and MAXIMA experiments (McGaugh 2000).

Still, despite all its successes, there are conceptual difficulties with MOND theory. The idea of modifying such an universal law as gravity is not straightforward and has many severe consequences. In a recent article Scott et al. (2001) review conceptual, empirical and cosmological difficulties with MOND. The main criticisms are: (*i*) Explicit violation of the equivalence principle resulting from the fact that in MOND inertial mass and gravitational mass are not the same. Derived from this (*ii*) momentum is not conserved and Newton's third law is violated. In fact, any multi component mass assembly faces difficulties in its dynamic description since (*iii*) gravity is no longer linear anymore and MOND does not allow for superpositions of gravitational fields. Evidently, since what applies to accelerations should also be valid for decelerations MOND suggests that (*iv*) all bodies are bound to each other, since gravitational forces decelerate any particle never less than a_0. The fundamental constant a_0 with the dimensions of acceleration that MOND introduces violates most of what fundamental physics relies on. It (*v*) violates Lorentz invariance because coordinate invariance, one of the fundaments of relativity, is not preserved. Also any concept of modelling forces by exchange particles fails. With the loss of coordinate invariance even the (*vi*) Cosmological Principle seems to not apply any more.

With these fundamental problems MOND has not won vast support within the astronomical community. Acceptance for MOND might improve if either a stronger theoretical framework is devised in which MOND is embedded or the concept of CDM comes into severe conflict with observations.