Introduction to Dark Matter

Excerpts from the Ph.D. Thesis *Quasars and Low Surface Brightness Galaxies as Probes of Dark Matter* (Uppsala University 2005)

Erik Zackrisson

Contents

1. Introduction to dark matter

1.1 The early history of dark matter research

During the last 70 years, a new paradigm has emerged in which the matter visible to us in current telescopes only represents a small fraction of the total amount present in the Universe. Most of the matter instead appears to be in some form which does not emit light, or at least very little. This is what is referred to as dark matter. To this day, the nature of this elusive component of the Universe remains a mystery.

The first detection of dark matter is attributed to Zwicky (1933), who measured the velocity dispersion of galaxies in the Coma cluster and found their velocities to far exceed that which could be attributed to the luminous matter in the galaxies themselves. The work of Zwicky on Coma was followed up by Smith (1936) for the Virgo cluster of galaxies. Once again, the velocities of its constituent galaxies indicated an unexpectedly high mass-to-light ratio.

Babcock (1939) used optical spectroscopy to measure the rotation of the Andromeda galaxy (M31), the nearest of the large galaxies in the vicinity of the Milky Way, and found the rotational velocity at large distances from the centre to be too large to be easily attributed to the luminous components.

From the velocities of the Milky Way and M31 towards each other, Kahn & Woltjer (1959) estimated the mass of the Local Group of galaxies (in which the Milky Way and M31 are the dominating members). By comparing this estimate to that expected from the luminous matter in these two objects, they concluded that most of the mass of the Local Group must be dark.

In the 1970s, dark matter became a well-recognized concept. The rotational evidence for dark matter in M31 grew stronger (e.g. Rubin & Ford 1970; Roberts & Whitehurst 1975) and kinematic investigations of other large disk galaxies (Einasto et al. 1974; Ostriker et al. 1974) gave similar results. These observations indicated that dark matter was a common feature among galaxies, but did not constrain its spatial distribution. Ostriker & Peebles (1973) showed that galactic disks by themselves would be unstable and suggested that they may be surrounded by massive, spherical halos. Hence, the important concept of dark halos, today believed to be common to all galaxies, was born.

The first conference devoted entirely to the dark matter problem was held in Tallinn, Estonia in January 1975 (for a review, see e.g. Einasto 2004). Already in these early days, a wide range of different candidates for the dark matter were considered. The first suggested were baryonic, i.e. made up of particles consisting of three quarks – like the protons and neutrons which contribute most of the mass to the matter familiar to us from everyday life. Dark-matter candidates in this category were ionized gas (Field 1972), very faint, low-mass stars (Napier & Guthrie 1975) and collapsed objects, like stellar black holes (Thorstensen & Partridge 1975). Cowsik & McClelland (1973) appear to have been the first to suggest a non-baryonic particle, the neutrino, as a candidate for the dark matter.

Once it was recognized that most of the matter in the Universe was dark, this component was expected to dictate the conditions for the formation of large structures like galaxies and galaxy clusters. The fact that relativistic dark matter particles (i.e. moving close to the speed of light in the early Universe) – today referred to as hot dark matter (HDM) – like standard, low-mass neutrinos, would have severe trouble in explaining the observed structures soon became evident. The advantages of cold dark matter (CDM), i.e. dark matter consisting of particles with non-relativistic velocities early on, was made clear by Primack (1982), Peebles (1982) and Blumenthal et al. (1984). Until this day, CDM holds the position as the leading dark-matter model, although a number of recent problems (see Sect. 1.6) with CDM may call for a revision of this scenario.

The first strong indications of dark matter in dwarf galaxies came in the early 1980s. Faber & Lin (1983) studied dwarf spheroidals and found them to contain large amounts of dark matter. Subsequent studies (for a review, see e.g. Mateo 1998) have in fact shown that dwarf galaxies have higher mass-to-light ratios than normal galaxies. Smaller stellar populations, like globular clusters, do on the other hand not appear to suffer from any significant missing matter problem.

At around the same time, the first robust evidence in favour of dark matter in elliptical galaxies came from observations of their X-ray luminous gas. By measuring the luminosity profile and temperature of this hot ($\sim 10^7$ K) gas, the gravitational potential can be derived by assuming the gas to be in hydrostatic equilibrium. Many of the early attempts concentrated on the giant elliptical galaxy M87 at the centre of the Virgo cluster. Since the dark halo of M87 is embedded in the dark matter of the surrounding cluster, there was however plenty of room for confusion about which system the detected dark matter should be attributed to. By the mid-1980s, a concordant picture had nonetheless emerged, in which both M87 (Stewart et al. 1984) and many other elliptical galaxies (Fabian et al. 1986) appeared to be surrounded by substantial amounts of unseen matter.

The road to establishing the presence, amount and distribution of dark matter in our own galaxy, the Milky Way, proved to be paved with more difficulties than in the case of external systems. In principle, the task is simply to measure the velocities of suitable test particles (e.g. gas clouds or stars) at known distances. Pioneering efforts in this field were made by Oort (1932, 1960). Due to the problems of determining accurate distances to objects whose velocities are known (or vice versa), and in correcting for the motion of the Sun itself around the centre of the Milky Way, large uncertainties are however introduced. For tracer objects not located in the Milky Way disk, e.g. halo stars, globular clusters and satellite galaxies, the assumed shape of their orbits (circular, elliptical or radial) can also have a pronounced impact on the outcome. These difficulties aside, a consensus has nonetheless been reached that the Milky Way does contain sizable amounts of dark matter, with a total mass on the order of $\sim 10^{12}\,M_{\odot}$ (see e.g. Cardone & Sereno 2005, and references therein). Its exact distribution is however still a matter of debate (see Sect. 1.5).

Apart from these methods, gravitational lensing – i.e. the effects associated with the gravitational deflection of light – has also played an important role in the study of dark matter. The notion that gravity can bend rays of light was proposed already by Newton, although the magnitude of this effect cannot be correctly predicted by Newtonian gravity. Instead, the full machinery of Einstein´s theory of general relativity is required. In 1919, Eddington measured the deflection of the light from a star as its ray of light crossed the edge of the sun during a total solar eclipse, confirming Einstein's predictions. Zwicky (1937) was a pioneer in suggesting that gravitational lens effects could also be used to measure the total masses of extragalactic objects. It would however take quite some time until this technique became observationally feasible. The first extragalactic gravitational lens system, the quasar 0957+561 was discovered in 1979 (Walsh et al. 1979). In this case, a background quasar is split into two optical images by a foreground galaxy (with some boost from the surrounding galaxy cluster). Since then, more than a hundred candidate multiply-imaged quasars have been detected. In 1986, Lynds & Petrosian (1986) announced the discovery of arclike features in galaxy clusters. These arcs were later identified as images of galaxies located far behind the foreground cluster and having been distorted by its gravitational field. Such gravitational arcs provide an independent, non-dynamical estimate of the total mass of the lens cluster, and have subsequently confirmed the need for dark matter to explain the gravitational potential of these objects (see e.g. Fort & Mellier 1994, for a review). A rich spectrum of other gravitational lens effects have also been discovered, many of which allows us to impose important constraints on the dark matter in the Universe.

1.2 Big Bang cosmology

Since the 1950s, the Big Bang scenario has held the leading position as the most successful model for the origin and evolution of the Universe. In this cosmology, the Universe started out extremely hot and dense some $14.1^{+1.0}_{-0.9}$ Gyr ago (Tegmark et al. 2004). Early on, there where no galaxies, no stars and no planets. The Universe was instead filled by a gas of subatomic particles at an extremely high density. As space expanded, the energy density dropped and the cosmic plasma cooled. After about 3 minutes, the Universe had cooled sufficiently to allow synthesis of the light elements H, He, Li and Be. This epoch of Big Bang nucleosynthesis (BBNS), after which most of the baryons were in the form of H and He, ended when the proton gas become sufficiently diluted by the expansion of the Universe to prevent further reactions. At around 240 000 years after the Big Bang, the Universe had reached a sufficiently low temperature ($\sim$ 4000 K) to allow protons and electrons to form neutral hydrogen (the so-called epoch of recombination). Shortly thereafter, at around 350 000 years after the Big Bang, hydrogen fell out of equilibrium with the photons, and the Universe became transparent to radiation. The Black body radiation originating from this cosmic plasma is still permeating the Universe in the form of the Cosmic Microwave Background Radiation (CMBR; often referred to as the "afterglow" of Big Bang) which can be observed at $T \approx 2.73$ K with radio telescopes.

In order for astrophysical objects like galaxies, star clusters and stars to form, density fluctuations must have been present from very early times. These seeds of structure formation could have originated from microscopic quantum fluctuations which were enlarged to cosmological scales during an epoch of extremely rapid expansion known as inflation (which, although not yet proved, is more or less accepted as a standard piece in the Big Bang scenario). At some point, these overdense regions become gravitationally instable, decoupled from the cosmic expansion and started to collapse. Eventually, stars formed inside these. Although the exact epoch of this occurrence is not well-determined observationally or theoretically, the first astronomical objects probably did not light up until $\sim$ 100 Myr after the Big Bang.

Due to the expansion of space, electromagnetic radiation emitted in the distant Universe is redshifted on its path towards us, so that the observed wavelength of light, $\lambda_{\rm obs}$, is larger than the wavelength at which it was emitted, $\lambda_{\rm emit}$. The longer the light path through the expanding cosmos, the larger is the amount of redshift induced. Redshift can therefore be used to determine the distances to astronomical objects. The redshift, z, is defined to be:

$$z = \frac{\lambda_{\rm obs}}{\lambda_{\rm emit}} - 1 = \frac{a_{\rm obs}}{a_{\rm emit}} - 1, \qquad (1.1)$$

where a is the cosmic scale factor (which can be set to $a_{\rm obs} = 1$ at the present time). Because of the finite speed of light, we are furthermore looking backwards in time as we aim our telescopes for distant regions of space. High redshift therefore simultaneously refers to the early and distant Universe, whereas low redshift indicates the local and recent Universe.

The Big Bang model for the origin and evolution of the observable Universe is supported by:

- The observed expansion of the Universe, inferred from the distance-dependent redshifts observed in the light received from galaxies outside the local Galaxy group (Hubble 1929);
- The observed abundances of the light nuclei ^{4}He, ^{3}He, ^{2}H and ^{7}Li, relative to ^{1}H, which are in good agreement with the predictions of BBNS;
- The existence of the CMBR, and its observed level of small-scale temperature anisotropy;
- The ages of the oldest astronomical objects (which sets a lower limit to the age of the Universe).

By adopting the cosmological principle, which assumes the universe to be spatially homogeneous and isotropic on large scales, a number of equations governing the evolution of the Universe can be derived from Einstein´s theory of general relativity. The resulting Friedmann equations, which form the basis of most contemporary cosmology, can be written:

$$\frac{\dot{a}^2 + kc^2}{a^2} = \frac{8\pi G\rho_{\rm tot}}{3}, \qquad (1.2)$$

and

$$\frac{2\ddot{a}}{a} + \frac{\dot{a}^2 + kc^2}{a^2} = -\frac{8\pi G p_{\rm tot}}{c^2}, \qquad (1.3)$$

where $\rho_{\rm tot}$ represents the total mass density of the Universe, $p_{\rm tot}$ the total pressure, and k the curvature parameter which determines the overall cosmic geometry. From these two, the Raychaudhuri (or acceleration) equation can be derived:

$$\frac{2\ddot{a}}{a} = -\frac{8\pi G}{3c^2}\sum_i(\rho_i c^2 + 3p_i), \qquad (1.4)$$

in which ρ_i and p_i represent the densities and pressures of the different components which contribute to the total density of the Universe. The diffuse components relevant for cosmology are assumed to behave as perfect fluids (with negligible viscosity), for which the equation of state is:

$$p = w\rho c^2, \qquad (1.5)$$

where w depends on the nature of the component. For relativistic matter and radiation, $w = 1/3$, whereas non-relativistic matter may be considered pressureless; $w = 0$. The equation of state regulates the density evolution of these cosmic fluids, according to:

$$\rho \propto a^{-3(1+w)}, \qquad (1.6)$$

which means that for non-relativistic matter $\rho_{\rm M} \propto a^{-3}$, whereas for radiation $\rho_{\rm rad} \propto a^{-4}$. The total density of the Universe is simply the sum over its i components:

$$\rho_{\text{tot}} = \sum_i \rho_i. \tag{1.7}$$

It is however more convenient to describe the different contributions to the current total density of the Universe with the use of the Ω parameter:

$$\Omega_i = \frac{\rho_i}{\rho_{\text{c}}}, \tag{1.8}$$

where the critical density ρ_{c} is the density required to make the Universe spatially flat ($k = 0$). The critical density at the present time is given by:

$$\rho_{\text{c}} = \frac{3H_0^2}{8\pi G}, \tag{1.9}$$

where H_0 represents the current value of the Hubble parameter ($H = \dot{a}/a$). This critical density corresponds to $\rho_{\text{c}} \approx 9.2 \times 10^{-27}$ kg m^{-3} for the currently favoured $H_0 \approx 70$ km s^{-1} Mpc^{-1}.

The most important contributions to the density ρ_{tot} of the Universe are often assumed be:

$$\rho_{\text{tot}} \approx \rho_{\text{M}} + \rho_{\text{rad}} + \rho_{\Lambda}, \tag{1.10}$$

where ρ_{M} represents the density contribution from non-relativistic matter and ρ_{rad} the corresponding contribution from relativistic matter or radiation. The last term, ρ_{Λ}, describes the density contribution from a so-called cosmological constant Λ with $w = -1$ (implying $\rho_{\Lambda} = \text{const}$). In the mid-1990s, supernova type Ia measurements revealed that we not only live in an expanding Universe, but that the expansion is currently progressing faster and faster (see e.g. Riess 2000, for a review). This revived the interest in the cosmological constant once introduced by Einstein to counterbalance the attracting gravitational effects of matter and to produce a model Universe which neither contracted nor expanded[1]. A value of this constant different from that required in Einstein's static scenario now appears to offer a possible explanation for the current acceleration of the Universe. Physically, this constant could correspond to a certain energy level associated with the vacuum. Although the available observations of supernovae type Ia and the CMBR are compatible with a true cosmological constant ($w = -1$, $\rho_{\Lambda} = \text{const}$), they are unable to rule out many contenders from the more general class of dark energy models (with $w(t) \neq 1$, $\rho_{\Lambda} \neq \text{const}$) introduced to explain the observed acceleration (for reviews, see e.g. Padmanabhan 2003; Peebles & Ratra 2003).

Current measurements of the cosmological parameters are consistent with a spatially flat ($k = 0$) Universe with $\Omega_{\text{tot}} \approx \Omega_{\text{M}} + \Omega_{\Lambda}$ (implying negligible contri-

---

[1] This was at a time before the discovery of the cosmic expansion (Hubble 1929). It was later recognized that the static Universe produced by fine-tuning the value of such a cosmological constant would be highly unstable, in the sense that the slightest perturbation would break the equilibrium and force the Universe into either contraction or expansion. It has been said that Einstein later referred to this cosmological constant as his "life´s greatest blunder". Given the tremendous recent interest in this parameter, one could however just as easily see it as another stroke of genius on his part.

butions from radiation and relativistic matter), where $\Omega_{\rm M} \approx 0.3$ and $\Omega_\Lambda \approx 0.7$.

1.3 Baryonic and non-baryonic dark matter

Recent inventories (Fukugita 2004; Fukugita & Peebles 2004) of the contributions to the cosmic energy content in the local Universe indicate that luminous matter (i.e. matter detected in emission – not absorption) contribute only $\Omega_{\rm lum} \approx 0.0051$ to the total energy budget, which corresponds to around 2% of the total matter contribution. This indicates that a baffling 98% of the matter in the Universe is sufficently dark not to be seen in current telescopes. The contribution from known stellar populations to the estimate of $\Omega_{\rm lum}$ is $\Omega_{\rm stars} \approx 0.0027$ and the contribution from gas (HI, HeI, H_2 and X-ray gas) $\Omega_{\rm gas} \approx 0.0024$[2].

Most of the mass of the matter making up planet Earth is in the form of three-quark particles known as *baryons* (e.g. the proton and neutron). The density of baryonic matter present on cosmic scales affects the reactions taking place during BBNS and also leaves an imprint in the CMBR. By comparing the observed primordial abundances of light elements to Big Bang nucleosynthesis models or by making a detailed analysis of the CMBR temperature anisotropies, the cosmic baryon density $\Omega_{\rm bar}$ can be derived. Investigations of this type currently indicate $\Omega_{\rm bar} \approx 0.045$ (e.g. Spergel et al. 2003). Since $\Omega_{\rm M} \approx 0.3$, this means that not only is most of the matter dark – only a minor fraction ($\approx 1/6$) of the mysterious dark matter can be in forms even remotely similar to the matter familiar to us from daily life. The fact that $\Omega_{\rm lum} < \Omega_{\rm bar}$ furthermore implies that the dark matter problem is twofold: both baryonic and non-baryonic dark matter must exist.

It has been argued (see Weinberg et al. 1997; Rauch 1998, and references therein) that most of the baryons (although with large uncertainties) at high redshift ($z \sim 2$–4) are likely to be in the form of ionized and neutral gas associated with the so-called Lyman-α forest absorbers. This would limit the baryonic dark matter problem to the form taken by the baryons in the local Universe. Some of the missing baryons at $z < 2$ have also been indirectly detected by absorption in the intergalactic medium, but estimates indicate that 35–45% of the baryons are still missing (Fukugita 2004; Nicastro et al. 2005).

1.4 The cold dark matter model

As the Universe expanded, it passed from a state of radiation- to matter-domination at $\sim 4.7 \times 10^4$ yr after the Big Bang (in the $\Omega_{\rm M} \approx 0.3$, $\Omega_\Lambda \approx 0.7$ scenario). If the Universe was purely baryonic, overdense regions would not be able to collapse until after recombination. Such a scenario is inconsistent with the density fluctuations evident from the CMBR and would lead to too slow structure formation. Non-baryonic (dark) matter can on the other hand

---

[2] The contribution from molecular gas could however have been underestimated – see Sect. 1.8.2 for further details.

collapse before this epoch. In this case, the details of structure formation depend on the properties of the dark matter particles. In the case of particles moving at relativistic velocities (i.e. moving with velocities $v \sim c$; so-called hot dark matter, HDM) at the epoch of matter-radiation equality, free-streaming out of overdense regions would prevent early formation of low-mass structures. Structure formation would in this case progress according to a top-down scheme, in which overdensities of galaxy-cluster scale would collapse first, whereas smaller subunits such as individual galaxies would form through fragmentation of these at much later epochs. Due to the observations of galaxies present already at high redshift, this scenario has now been dropped in favour of a bottom-up scheme, in which low-mass objects form first, and larger structures form through subsequent mergers and collapse. As was realised in the early 1980s, this can be achieved by non-baryonic matter which is non-relativistic (i.e. moving with $v \ll c$) at the epoch of radiation-matter equality. This component, known as cold dark matter (CDM), is still the leading contender for the non-baryonic dark matter of the Universe, and has been remarkably successful in explaining the observed large scale structures of the Universe. For a particle species in thermal equilibrium in the early Universe, the particle mass must be > 1 keV in order for it to qualify as CDM. At masses of $\ll 1$ keV, it would instead behave as HDM. Current cosmological observations constrain the non-baryonic matter component of the Universe to have an equation of state with $-1.5 \times 10^{-6} < w < 1.13 \times 10^{-6}$ (Müller 2005), i.e. in excellent agreement with the CDM hypothesis ($w = 0$). The currently favoured cosmology (with $\Omega_{\mathrm{M}} \approx 0.3$, $\Omega_{\Lambda} \approx 0.7$), in which most of the matter is assumed to be CDM, is therefore often referred to as the ΛCDM model.

Apart from non-relativistic velocities (dynamical "coldness"), a number of additional dark matter properties are usually assumed in the CDM scenario. The CDM particles[3] are also assumed to:

- be collisionless, meaning that they interact through gravity only and have no other significant self-interactions;
- be dissipationless, meaning they cannot cool by radiating photons (as opposed to normal baryonic matter);
- be long-lived, meaning that their lifetimes must be comparable to or longer than the present age of the Universe;
- behave as a perfect fluid on large scales, meaning that the granularity of the dark matter is sufficiently fine not to to have been directly detected yet through various effects (for a review, see Carr & Sakellariadou 1999).

In addition, the CDM model for structure formation assumes the primordial density fluctuations to be adiabatic and to follow a scale-invariant power spectrum.

---

[3] Here, a "particle" should not interpreted as something which is necessarily microscopic on human mass and length scales, but rather on cosmic ones. Hence, a dark matter particle can refer to a subatomic particle as well as a huge astrophysical object.

1.5 The spatial distribution of dark matter

Observations of the large scale distribution of galaxies and simulations of the clustering of dark matter have produced a reasonably coherent picture, in which the CDM is distributed in a foam/soap-bubble/spiderweb-like structure of voids, filaments and walls with characteristic sizes of ~ 100 Mpc. In high-density regions, almost spherical structures known as dark matter halos are expected to form. Inside these, baryons collapse through dissipation to form luminous galaxies of stars and gas. In the CDM picture, the dark halos merge in a hierarchical fashion into larger and larger halos. Today, the Universe is filled with dark halos with masses ranging from dwarf galaxy ($\sim 10^6\ M_\odot$) to giant galaxy cluster ($\sim 10^{15}\ M_\odot$) scale. Inside each of the more massive dark halos, smaller subhalos reside, so that each cluster-mass halo is filled with a large number of galaxy-mass halos, and each galaxy-mass halo with halos of dwarf-galaxy mass. The converse is however not necessarily true, as most galaxy-mass dark halos are in fact not associated with rich clusters, but located in loose groups or in the so-called "field". In Fig. 1.1, the distribution of galaxies within large-scale dark matter structures is illustrated schematically.

The case for the existence of dark halos around galaxies is nowadays rather strong. As originally shown by Ostriker & Peebles (1973), galactic disks would quickly turn into giant bars without the stabilizing influence of a massive, spheroidal component such as a dark halo. In principle, a baryonic bulge could also suffice (Athanassoula & Sellwood 1986), but not all disk galaxies appear to have these. The weak, statistical image distortions imposed on distant objects in large galaxy catalogues by the matter distribution in foreground objects (so-called weak gravitational lensing) also confirm the dark matter distribution to be reasonably consistent with CDM halos (see Hoekstra et al. 2004, for a review).

It must however be emphasized that many phenomena which were once considered to be telltale signs of dark halos have since found alternative explanations. Many disk galaxies exhibit a phenomenon known as HI flaring, in which the distribution of neutral hydrogen in the direction perpendicular to the plane of the disk increases with radius from the centre of the galaxy. As the velocity dispersion of the gas does not increase with radius, this indicates that the mass distribution must become rounder (i.e. less disk-like) further out from the centre (van der Kruit & Shostak 1984). This argument has often been used to argue that an increasing mass fraction must be located outside the visible thin disk at large radii – i.e in the form of a dark halo. It has however been suggested that a thick dark matter disk would work just as well (e.g. Olling 1996). Warps in galactic disk, i.e. a disk inclination which changes with radius, have also been used to argue both for and against dark matter halos. These features can for instance be induced by gravitational forces during galaxy interactions or from gas accretion, and are very common among disk galaxies. Even seemingly isolated galaxies have warps. This implies that the warps must be frequently generated or very long-lived. Although dark halos can prevent the rapid decay of the warp expected from differential rotation within the disk (Tubbs & Sanders 1979), massive dark matter disks may also do the trick (Revaz & Pfenniger 2004).

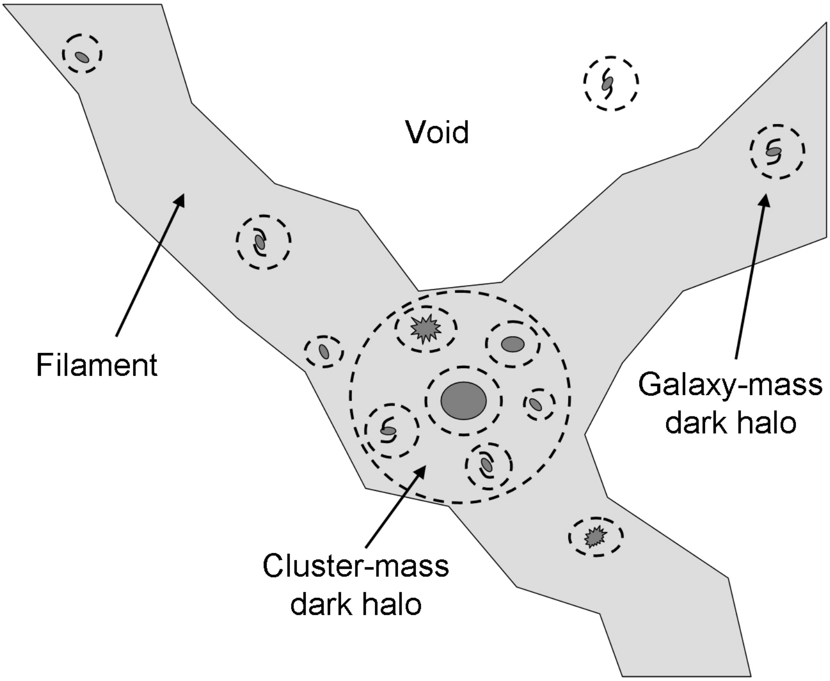

Figure 1.1: Schematic illustration of the distribution of galaxies and dark matter on large scales. A string of galaxy-mass dark halos (containing galaxies of varying morphological type) are located in medium-density filaments leading into a larger halo of galaxy-cluster mass. At the centre of the cluster, a giant elliptical galaxy has formed from the merging of several smaller galaxies. A number of galaxy-mass subhalos are orbiting the cluster centre. In the low-density void outside the filaments, only a single galaxy is found. In this figure, only one hierarchy of subhalos is shown (i.e. no dwarf-mass dark halos inside the galaxy-mass ones). The different objects are not plotted to scale.

The location of the dark baryons in the CDM picture is still something of an open question. From a theoretical point of view, the baryons are not expected to fully trace the overall distribution of matter. Instead, hydrodynamic simulations indicate that the baryon fraction in high-density regions like dark matter halos should actually be lower than the cosmic average, and that substantial reservoirs could exist in the medium-density regions of the intergalactic medium where it would be very difficult to detect (e.g. Cen & Ostriker 1999; He et al. 2005). Whether this really is the case remains to be seen, and the possibility that large quantities of baryonic dark matter may also be present inside galaxies should be kept in mind. Due to the dissipational nature of baryons, the dark baryons need not follow the density profile of CDM halos, and could easily end up inside galactic disks. A number of investigations do in fact seem to favour such a scenario, e.g. the analysis of spiral and bar structure in the disk of the blue compact dwarf galaxy NGC 2915 (Masset & Bureau 2003), the number of spiral arms observed in low surface brightness galaxies (Fuchs

2003) and the curious correlations reported between HI mass density and total mass density in spiral galaxies (see e.g. Bosma 2002, and references therein).

Not even in the case of the Milky Way is the situation entirely clear. By studying the spatial distribution and velocities of disk stars in the direction perpendicular to the plane of the Milky Way disk, Oort (1932, 1960) derived the mass density in our vicinity of the disk and found it to exceed the visible mass by roughly a factor of two. This would indicate that at least some of the dark matter in the Milky Way is distributed in a disk-like structure, i.e. not in a dark halo. The constraint on the mass distribution of the Milky Way imposed by the local matter density is commonly referred to as the Oort limit, although its exact value remains controversial. Since many subsequent investigations have failed to confirm the existence of substantial amounts of dark matter in the vicinity of the sun (e.g. Kuijken & Gilmore 1989; Bienaymé 1999), the Oort detection has fallen into disrepute. Most investigations in this field have however assumed plausible disk dark matter to be distributed in a very thin structure. According to recent claims by Kalberla (2003), the available data does in fact favour a mass distribution in which the density and dynamics of the Milky Way are dominated by a thick dark matter disk out to a radius of 35 kpc from the centre.

1.6 Problems with cold dark matter

Despite a remarkable success in explaining the large scale structure of the Universe, the CDM model is currently facing a number of potentially serious problems on the scales of individual dark halos. It must however be emphasised that many of these problems may in the end turn out to be related to how CDM halos and CDM-baryon interactions are simulated, rather than problems with the CDM itself.

1.6.1 Dark halo density profiles

Numerical N-body simulations based on CDM predict that dark halos should exhibit a spherically averaged density profile (Navarro, Frenk, & White 1996, 1997 – commonly referred to as the NFW profile) given by:

$$\rho(R) = \frac{\rho_{\mathrm{i}}}{(R/R_{\mathrm{S}})(1+R/R_{\mathrm{S}})^2}, \tag{1.11}$$

where R_{S} is the characteristic radius of the halo and ρ_{i} is related to the density of the Universe at the time of collapse. Under the assumption of a spherical halo, this density profile corresponds to a rotation curve (i.e. the circular rotational velocity required for rotational support at each radius) given by:

$$V_{\mathrm{C}} = V_{200}\sqrt{\frac{\ln(1+cx) - cx/(1+cx)}{x[\ln(1+c) - c/(1+c)]}}, \tag{1.12}$$

where $x = R/R_{200}$. R_{200} is defined as the radius inside which the mean density of the halo is 200 times the critical density of the Universe, and V_{200} the circular velocity required for rotational support at that point. This NFW circular velocity curve is defined by two parameters, the concentration c, and V_{200}. The two are not independent, but related through the assumed cosmology. In the case of ΛCDM, the relation can be approximated by:

$$\log c = 1.191 - 0.064 \log V_{200} - 0.032 (\log V_{200})^2. \tag{1.13}$$

Current simulation indicate that cosmic scatter among CDM halos correspond to $\sigma(\log c) = 0.18$ (Bullock et al. 2001).

The problem with this prescription is that the predicted rotation curves appear inconsistent with the observed rotation curves of dwarf and low surface brightness galaxies (see e.g. de Blok & Bosma 2002, and references therein), in which the dynamics are believed to be minimally affected by luminous matter. The NFW profile produces very high mass densities in the central regions of the halos, predicting rotation curves which rise much steeper than observed at small radii. In the innermost kpc, the NFW profile furthermore displays a dramatic rise in density, a so-called density cusp, whereas most observations so far have indicated real halos to exhibit a core of almost constant density. Instead of the NFW profile, the observations typically favour a density profile characteristic of a pseudo-isothermal sphere with a central core of constant density:

$$\rho(R) = \frac{\rho_0}{1 + (R/R_C)^2}, \tag{1.14}$$

where ρ_0 is the central density of the core and R_C the core radius. This density profile corresponds to a circular velocity rotation curve:

$$V_C = \sqrt{4\pi G \rho_0 R_C^2 \left[1 - (R_C/R) \arctan(R/R_C)\right]}. \tag{1.15}$$

The difference between core- and cusp-like density profiles is illustrated in Fig.1.2.

The seriousness of the core/cusp discrepancy between the CDM predictions and observations in the innermost kpc is still somewhat unclear, as the N-body simulations have not yet reached the same resolution as the observations (Power et al. 2003; Navarro et al. 2004) and since many of the current measurements of the central density slope may be biased by systematic errors (e.g. Swaters et al. 2003; Spekkens & Giovanelli 2005). The shape of the overall rotation curve, as dictated by the c parameter in the NFW formalism, provides a more robust test of the CDM model, although the non-spherical shapes of CDM halos (see Sect. 1.6.3) may complicate the analysis in ways not yet taken into account (Hayashi et al. 2004). Another way to reconcile CDM theory with observations is to assume that dwarf and low surface brightness galaxies, which have been the prime targets in these investigations, represent the low-density tail of the halo distribution (Zentner & Bullock 2002; Jimenez et al. 2003; Bailin et al. 2005), or to assume that the dark matter which dominates the inner regions of these galaxies is baryonic (e.g. Combes 2004), possibly

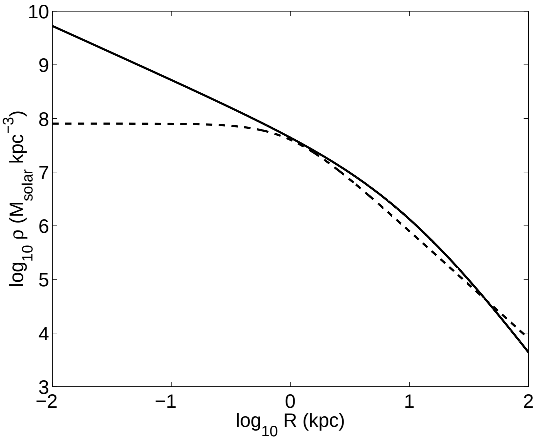

Figure 1.2: The density profile of an NFW halo with $R_{\rm S} = 10$ kpc (solid) compared to that of an pseudo-isothermal sphere with $R_{\rm C} = 1$ kpc (dashed). The total mass of both halos inside a radius of 100 kpc is 10^{11} $M_{\odot}$. While the density of the NFW halo continues to rise within the central kpc (a so-called density cusp), the pseudo-isothermal sphere displays a core of constant density.

making them prone to one of the many baryonic mechanisms which have been suggested for decreasing the central mass density of galaxies (e.g. Athanassoula 2004). A more detailed discussion on possible solutions to the CDM density profile problem can be found in paper V.

1.6.2 Dark halo substructure

The CDM scenario predicts a dark halo mass function (describing the number of halos n of a given mass M inside a certain volume) of the approximate form $n(M) \propto M^{-2}$. This means that the number of low-mass halos should outnumber those of high mass by a large factor. In particular, each galaxy-mass halo should contain a large number of subhalos (corresponding to $\leq 10\%$ of its mass; e.g. van den Bosch et al. 2004) in the dwarf-galaxy mass range. Such halo substructure would help to explain previous problems in understanding the exact flux ratios between the images of quasars subject to strong gravitational lensing, and some even claim that the anomalous flux ratios seen in these systems constitute an indirect subhalo detection (see Mao 2004, for a review).

The problem becomes apparent once one tries to attribute the subhalos to actual galaxies. In the case of the Milky Way, CDM predicts a factor of 10–100 more satellite galaxies than observed, if each subhalo corresponds to a luminous dwarf galaxy (Moore et al. 1999).

One way out of this dilemma is to assume that some of these subhalos correspond to so-called dark galaxies (e.g. Trentham et al. 2000; Verde et al. 2002), i.e. objects of (dwarf) galaxy mass which either do not contain baryons or in which the baryons have not formed stars. Possible mechanisms for the latter scenario could be ionization by the ultraviolet background (Dong et al. 2003) or very high angular momentum in a disk (Jimenez et al. 1997). A couple of candidates for such dark galaxies, which contain gas but very few stars, have recently been identified (Simon et al. 2003; Minchin et al. 2005).

1.6.3 Shapes of dark matter halos

The dark halos formed in the framework of the CDM scenario are not predicted to be perfectly spherical, but instead triaxial, with three principal axes a, b, c ($a > b > c$), where the equatorial axis ratio b/a is referred to as ovalness, and the vertical-to-equatorial axis ratio c/a as flattening. Observationally, the shapes of galaxies can be estimated using a host of techniques like stellar kinematics, geometry of X-ray isophotes in elliptical galaxies, kinematics of polar ring galaxies, HI flaring and gravitational lensing (see Sackett 1999, for a review), which mostly seem to indicate $b/a \geq 0.8$ for the ovalness, but a rather large scatter for the flattening ($c/a \approx 0.3$–1.0). The situation is severely complicated by the fact that the axis ratios need not be constant as a function of distance from the halo centre, and that different methods are sensitive to different regions of the halo. Whereas some studies have indicated that the dark halo of the Milky Way must be nearly spherical (e.g. Ibata et al. 2001), CDM predictions for a galaxy-mass halo have yielded $< c/a > \approx 0.55$ with $\sigma(c/a) \approx 0.15$ (Jing & Suto 2002). Weak gravitational lensing has on the other hand yielded an average projected $< c/a >= 0.66\pm^{0.07}_{0.05}$ (Hoekstra et al. 2004), which is usually claimed to be in reasonable agreement with CDM. The CDM simulations responsible for this prediction are however dissipationless, and do not take the effects of baryon cooling into account. When such effects are included, the dark halos become substantially more spherical, especially in the innermost region (Kazantzidis et al. 2004). The projected ellipsoid of the dark halo does furthermore not need to be aligned with that of the baryons at all radii. Due to the enormous complexities involved in both observations and simulations in this field, it is not obvious that the available measurements of dark halo shapes pose any real threat to the CDM paradigm at the current time.

1.6.4 The overcooling or angular momentum problem

Forming disks in reasonable agreement with observed galaxies has proved a big problem in current CDM simulations (see Primack 2004, for a review). The distribution of angular momentum among the mass particles in CDM halos appears to have the wrong form to make disk galaxies with an exponential surface density profile (Bullock et al. 2001). Simulations of disk formation inside CDM halos furthermore appear to be subject to overcooling, meaning that the baryons lose too much angular momentum to the dark matter, giving rise to baryonic disks which are much too small. The latter problem is believed to arise in the process when the dark matter halo is assembled from smaller subunits. If the baryons inside each merging subhalo have dissipated, i.e. have become concentrated to the centre, then the CDM in its outer parts will be tidally stripped, causing the baryons to lose angular momentum by dynamical friction. A possible solution is that feedback from supernovae may prevent the gas from cooling to the centre of the small halos, hence making the baryons retain much of their angular momentum (Maller & Dekel 2002). Hydrodynamical simulation which convincingly demonstrate that this may entirely solve all aspects of the angular momentum problem have however not yet emerged. D’Onghia & Burkert (2004) point out that while feedback may possibly solve the angular momentum catastrophe in halos subject to major mergers in the past, massive baryonic bulges are also formed in the process. For bulgeless galaxies, located inside halos which have not experienced any major mergers, a different solution appears to be required. The baryons in these systems should have retained their angular momentum, yet the disks formed in hydrodynamical simulations of such halos still contains too little angular momentum to be consistent with observed galaxies without a bulge.

1.7 Alternatives to cold dark matter

To resolve the various problems faced by CDM, a number of remedies have been suggested, varying from quite modest to very radical modifications of the assumptions going into the CDM model. A number of these are briefly reviewed below.

1.7.1 Warm dark matter

A dark matter species with velocities intermediate between those of HDM and CDM, so-called warm dark matter (e.g. Bode et al. 2001), would prevent gravitational clustering on small scales and inhibit the formation of such structures. This could potentially lower the densities in the centres of dark halos and reduce the number of subhalos, thereby removing two of the most serious problems faced by CDM. For particles which have been in thermal equilibrium in the early Universe, the mass should be around ~ 1 keV in order for them to act as warm dark matter.

1.7.2 Mixed dark matter

Mixed dark matter, i.e. a mixture of cold and hot dark matter, became fashionable for a few years in the mid-1990. The main virtue of this scenario was that it could reconcile the CMBR observations of the time with (apparently spurious) reports of neutrino masses in the 20–30 eV range (for a review, see Primack 2001). Interest in mixed dark matter declined, however, once the ΛCDM model entered the stage and provided a superior explanation for supernova type Ia data, the CMBR anisotropies and the observed large scale structure of the Universe at both high and low redshift. While neutrinos are no longer believed to contribute substantially to the energy density of the Universe (see Sect. 1.8.3), they do appear to have non-zero masses in the right range to make them act as HDM. A small contribution from HDM (with $\Omega_{\mathrm{HDM}} \sim 0.01$) is still viable within the ΛCDM picture, and could help to lower the central densitites of dark halos somewhat (e.g. Zentner & Bullock 2002).

1.7.3 Self-interacting dark matter

Introducing non-gravitational interactions among the dark matter particles gives rise to a complex phenomenology, the details of which have not yet been fully worked out. Elastic collisions among the dark matter particles could however both reduce the central halo densities and inhibit the formation of halo substructure, depending on the scattering cross-section (Spergel & Steinhardt 2000; Ahn & Shapiro 2004). Although a number of observational constraints have been imposed on the strength of the dark matter self-interaction, seemingly closing most of interesting parameter space, these constraints may not be as strong as originally claimed (see Ahn & Shapiro 2004, for a review).

1.7.4 Self-annihilating or decaying dark matter

Dark matter particles which self-annihilate (Kaplinghat et al. 2000) upon collision would decrease the densities in regions where collisions are most likely to occur, i.e. in the central regions of dark halos. Alternatively, a component of dark matter which decay into radiation or relativistic particles during early stages of structure formation could also inhibit the formation of dense halo centres (Cen 2001). Although halo substructure will still form in such scenarios, star formation in subhalos may be quenched due to expansion of subhalos following the evaporation of dark matter. If some component of the dark matter is decaying into hydrogen-ionizing radiation at the current time, this could also help explain the scale-height of ionized gas in the Milky Way disk, which has long proved difficult to reconcile with known ionization sources in our own galaxy (Sciama 1990).

1.7.5 Fuzzy dark matter

Dark matter particles with low masses but extremely large effective sizes (e.g. on the same order as the constant density cores found in the centre of many galaxies) cannot be concentrated on small scales, which would inhibit the formation of central density cusps and halo substructure (e.g. Hu et al. 2000).

1.7.6 Modified gravity

As essentially all the evidence for the existence of dark matter is gravitational (but see Sect. 1.9 for different views), a viable alternative to modifying some of the assumptions of the CDM model could be to postulate that dark matter does in fact not exist, and that it is the theory of gravitation that requires modification. Several attempts down this route have in fact been made (see Aguirre et al. 2001a, for a review). The most successful so far is Modified Newtonian Dynamics (MOND; Milgrom 1983), in which Newton's law of gravity is modified in the regime of small accelerations. In Newtonian gravity, the acceleration a of a test particle in the gravitational field of some mass M at distance R is given by:

$$a = \frac{MG}{R^2}. \tag{1.16}$$

In MOND, this expression is replaced by:

$$\mu(a/a_0)a = \frac{MG}{R^2}, \tag{1.17}$$

where a_0 is a parameter which regulates the acceleration at which the standard Newtonian formula breaks down. Here, $\mu(a/a_0)$ is a function with the property that $\mu(a/a_0) \approx 1$ when $a/a_0 \gg 1$ and $\mu(a/a_0) \approx a/a_0$ when $a/a_0 \ll 1$. Hence, in the limit of small accelerations (e.g. at large distances from the centre of a disk galaxy, where rotation curves indicate the presence of dark matter), the Newtonian expression for a is replaced by:

$$\frac{a^2}{a_0} = \frac{MG}{R^2}. \tag{1.18}$$

This simple formalism has been remarkably successful in explaining the dynamics of galaxies without the need for dark matter (see Sanders & McGaugh 2002, for a review). A recent analysis (McGaugh 2004) indicates that it may even be consistent with the CMBR results from the WMAP satellite, which are usually taken as strong support of the standard ΛCDM scenario. Until recently, MOND was just an effective modification of Newtonian physics, with no known relativistic extension from which to make definite predictions about phenomena like cosmic expansion and gravitational lensing. The recent relativistic treatment of MOND by Bekenstein (2004) has however changed this picture, allowing new tests of this interesting model of modified gravity.

The most serious problem with MOND is that it appears unable to fully explain the properties of galaxy clusters (e.g. Aguirre et al. 2001b), which still seem to require a component of dark matter. While advocating both modified gravity *and* dark matter in order to save MOND may seem like invoking the tooth fairy twice, solutions of this kind have nonetheless been proposed (Sanders 2003).

1.8 Dark matter candidates

Here, a short introduction is given to some of the dark matter candidates that have been discussed in the literature during the last decade. Due to the vastness of this topic, the list presented here is however by no means complete.

1.8.1 WIMPs and MACHOs

A substantial part of the dark matter literature revolves around two important acronyms, WIMPs and MACHOs. The WIMPs, or Weakly Interacting Massive Particles, are small, non-baryonic particles which interact only through gravity and the weak nuclear force. Their masses are usually assumed to lie in the GeV–TeV range (a proton, by comparison, has a mass of 0.938 GeV and an electron a mass of 0.511 MeV), which would make them sufficiently slow-moving at the time of matter-radiation equality to act as CDM. Because of their lack of strong interaction with normal matter and lack of interaction through electromagnetism, they would appear dark in current telescopes, unless they happen to decay or annihilate into photons. Although there are no known particles within the standard model of particle physics which correspond to WIMPs, supersymmetric extensions contain a host of potential WIMP candidates.

The MACHOs (Massive Astrophysical Compact Halo Objects[4]) are large astrophysical objects (which for some reason do not emit much light) with masses substantially larger than those of WIMPs. Although the acronym was originally proposed with baryonic objects like failed stars in mind, many non-baryonic candidates can in fact behave as MACHOs. Therefore, contrary to a wide-spread misconception in the astronomical community, the MACHO populations that can be probed through microlensing effects (see Sect. 1.9.2) are not necessarily subject to constraints on the baryonic mass fraction of the Universe, and can in principle constitute *all* of the dark matter (although current constraints make this seem unlikely). Certain kinds of MACHOs could furthermore have a sufficiently small interaction with the baryonic content of the Universe to effectively behave as CDM. It should also be noted that – despite the meaning of the acronym – MACHOs not associated with dark matter halos (but rather with low-density regions like filaments) are nowadays also being considered.

Of course, not all dark matter candidates fall within the definitions of WIMPs and MACHOs. Some of those described in the following are neither, while others are both.

1.8.2 Baryonic candidates

In the standard Big Bang scenario, no more than $\sim 1/6$ of the cosmic matter density can be attributed to baryons. According to current matter inventories (e.g. Fukugita 2004; Fukugita & Peebles 2004), around $\sim 1/3$ of these

---

[4] This acronym was suggested by astronomers as a humorous counterstrike to the WIMPs favoured by particle physicists.

baryons are unaccounted for in the local Universe. While making up only a small fraction of the matter in the Universe, this baryonic dark matter can still be important for understanding e.g. the properties of galactic disks (see Sect. 1.5).

Faint stars and stellar remnants

Very faint, low-mass stars such as red and brown dwarfs could in principle constitute part of the baryonic dark matter if located at sufficiently large distances, e.g. in the dark halo of the Milky Way. Brown dwarfs are objects which are too light ($< 0.09\ M_\odot$) to start thermonuclear reactions, whereas red dwarfs are just massive enough ($0.09 < M/M_\odot < 0.2$) to burn hydrogen in their cores. Direct searches for the latter have indicated that these contribute less than 1% to the mass of the Milky Way dark halo. The feeble luminosity of brown dwarfs comes from conversion of potential energy into radiation by contraction. Since this makes them even fainter than red dwarfs, they cannot be detected at equally large distances. To estimate their contribution to the dark halo, a number of assumptions about the stellar intial mass function must be made. Although most studies infer an upper limit on brown dwarfs of the same order as that of red dwarfs, it is in principle possible that the initial mass function may be substantially different at large distances from the Galactic disk. Microlensing surveys do however constrain brown dwarfs to contribute $\leq 25\%$ (e.g. Afonso et al. 2003) to the mass of the dark halo.

At the end of their lifetimes, stars may form very faint remnants, such as white dwarfs, neutron stars and stellar black holes. White dwarfs are $\leq 1.4\ M_\odot$ mass objects, which are the end products of stars with masses $0.2 < M/M_\odot < 8$. While having the right masses to explain the MACHO detections in the halo of the Milky Way (Sect. 1.9.2), they are no longer favoured as baryonic dark matter candidates. Although white dwarfs are very faint, their progenitors are bright. Having a large contribution to baryonic dark matter from white dwarfs today would hence imply large contributions from their progenitors to the light of high-redshift galaxies and to the infrared extragalactic background radiation, which are not seen. On their way to becoming white dwarfs, the progenitors furthermore pass through a planetary nebula phase, during which heavy elements are ejected into the interstellar medium. The degree of metal pollution that would correspond to a large white dwarf population today is too high to be consistent with observations. Finally, having a large population of white dwarfs today would at some point in the history of the Universe require a stellar initial mass function which would produce too many supernovae type Ia. Neutron stars are formed as end products of $8 < M/M_\odot < 30$ stars and stellar black holes from $> 30\ M_\odot$ progenitors. At the end of their lifetimes, the progenitors stars of these objects have however gone through a supernova type II phase, during which copious amounts of metals are ejected into the interstellar medium. These candidates therefore face a metal pollution problem even more serious than that of white dwarfs.

For a review of faint stars and stellar remnants as baryonic dark matter, see Freese (2000).

Cold gas clouds

Molecular hydrogen is by itself very difficult to detect in space, and is usually traced through the CO molecule. The CO–H_2 conversion factor is however metallicity-dependent and very uncertain at low metallicities. The detectability of H_2 furthermore decreases if it is not distributed uniformly, but rather in small clouds. Pfenniger et al. (1994) and Pfenniger & Combes (1994) have suggested that the baryonic dark matter could be in the form of cold planetary-mass clouds (or clumpuscules) of H_2 distributed in a fractal, self-shielding way in the outer regions of galactic disks. If such clouds are also assumed to populate the dark halo, they may develop a photoionised skin due to radiation from disk stars and could explain the extreme scattering events seen in radio observations of quasars (Walker & Wardle 1999). While such clouds are generally believed to be too diffuse to be detectable through gravitational microlensing effects, they could be detectable through gas lensing or plasma lensing (Draine 1998; Walker & Wardle 1999). Cosmic ray interactions with small clusters of such dense gas clouds could also give rise to gamma-ray emission, and Walker et al. (2003) argues that the unidentified gamma-ray sources detected by EGRET can be attributed to such a population. Star formation is known to take place in molecular clouds, and the idea of H_2 as baryonic dark matter has recently gained further momentum by the discovery of star formation activity in the outer regions of the M31 disk (Cuillandre et al. 2001), where no molecules have been detected, indicating that dark H_2 may in fact be a reality.

Warm/Hot intergalactic gas

Part of the baryonic dark matter could be associated with the filamentary web which connects the the dark halos of galaxy groups and clusters. Hydrodynamical simulations suggests that the baryons in these structures should be in the form of diffuse gas, which is heated and ionized by shocks to such a degree that it becomes transparent in the optical and near-IR. This Warm/Hot (10^5–10^7 K) Intergalactic Medium (WHIM) can however be detected through emission or absorption at far-UV and X-ray wavelengths. Recent detections of X-ray absorption features associated with the WHIM towards low-redshift blazars indicate that essentially all of the missing baryons may be located in the WHIM (Nicastro et al. 2005), but the errorbars are still very large.

Rydberg matter

Rydberg matter is the name given to a condensed phase of low density density matter, which can form long chains of planar clusters consisting of atoms or molecules. In space, Rydberg matter is likely to be made primarily out of atomic and molecular hydrogen. Due to its highly excited state and extremely long lifetime, Rydberg matter would be largely transparent to light and could act as baryonic dark matter (Badiei & Holmlid 2002). Deexciting Rydberg matter could furthermore possibly explain certain unidentified interstellar emission features in the infrared (Holmlid 2000).

1.8.3 Non-baryonic candidates

Listed here are both candidates which are intrinsically non-baryonic (e.g. neutrinos) as well as those that are intrinsically baryonic but through some clever mechanism evade the constraints on the cosmic baryon density (e.g. baryons in folded branes).

Neutrinos

Neutrinos represent the only kind of non-baryonic matter which contributes non-negligibly to the cosmic energy density and is actually known to exist. The three known neutrino species (ν_{e}, ν_τ and ν_μ) are however constrained by laboratory bounds and the CMBR to be very light ($\sum m_\nu \leq 0.7$ eV), corresponding to a contribution to the cosmic energy budget of $0.001 \leq \Omega_\nu \leq 0.014$. Standard neutrinos in this mass range would act as HDM and are therefore not suitable candidates for the dark matter of the Universe. A fourth, so-called sterile neutrino – which could act as CDM – has been postulated from time to time to solve various problems in neutrino physics, but does not seem to be favoured by the most recent experiments (see e.g. Valle 2004).

Axions

The axion, named after a laundry detergent, was proposed in the late 1970s to blot out a disturbing stain on the face of quantum chromodynamics (QCD), the theory which describes the strong interactions between quarks. The axions favoured as dark matter candidates interact so weakly that they were never in thermal equilibrium in the early Universe. Because of this, axions would serve as CDM, despite having been constrained to be very light (10^{-6}–10^{-2} eV).

Due to the possibility of axion-photon conversion in the presence of magnetic fields, axions have been proposed as an alternative to dark energy for explaining the supernovae type Ia data. As the light from these lighthouses cross great distances to reach us, a certain fraction of their photons may be converted into axions, making high-redshift supernovae type Ia appear dimmer than they really are. For some of the pros and cons of axions in particle physics and cosmology, see Banks et al. (2003).

Supersymmetric particles

Supersymmetry is a high-energy extension of the standard model of particle physics, in which a symmetry between bosons (particles with integer spin) and fermions (particles with half-integer spin) is assumed to exist. In this picture, every standard fermion is accompanied by a bosonic superparticle, and every standard boson by a fermionic one. For the superpartners of standard fermions, an “s” is added as a prefix to the name (i.e electron becomes selectron), while for the superpartners of standard bosons, the last syllable of the name is replaced by “ino” (i.e. photon becomes photino). Hence a zoo of new particles is predicted to exist (e.g. sneutrinos, gluinos, squarks), and may have been created in great numbers in the early universe. A supersymmetric particle cannot decay into normal particles only, which means that the lightest supersymmetric particle must be stable. This would make it a good candidate for the non-baryonic dark matter. The supersymmetric dark matter candidate generating the most articles is the neutralino, but other options such as the axino (the supersymmetric partner to the axion) and the gravitino are also viable options. If supersymmetric particles exist, they may be detected in upcoming high energy particle colliders like the Large Hadron Collider at CERN (planned to be operational in 2007), provided that their mass is lower than a few hundred GeV. For reviews of the phenomenology of supersymmetric dark matter, see Bergström (2000) and Feng (2005).

Mirror matter

The interactions of elementary particles obey a number of symmetries, like rotational, translational and Lorentz invariance. A number of fundamental particles, like the neutrino and the positron, have in fact been predicted (and subsequently found) by the very existence of these symmetries. There are however two such symmetries, space reflection symmetry (parity) and time reflection symmetry, which do not appear to correspond to the interactions of known particles. These symmetries can however be implemented by postulating the existence of so-called mirror particles, which are not produced in laboratory experiments because of their very weak coupling to ordinary particles. The existence of this "mirror world" gives rise to a complicated cosmology in which the dark matter may consist of mirror baryons. Mirror baryons are expected to form astronomical objects like mirror-stars, mirror-planets and perhaps even mirror-galaxies, which we will not be able to see in our telescopes. If BBNS took place slightly earlier in the mirror sector, then the ratio of mirror-He to mirror-H may be substantially higher than in our familiar Universe. This could give rise to radically different evolution of astronomical objects in the mirror sector, possibly explaining the almost spherical dark halos as due to mirror-gas heated by mirror-supernovae. This mirror-matter cosmology has been claimed to explain a wide range of phenomena, like the annular modulation signal (Sect 1.9.1), the detection of MACHOs (Sect 1.9.2), the Tunguska impact and the anomalous deceleration detected by the Pioneer spacecrafts. See Foot (2004a) for a review.

Primordial black holes

Primordial black holes can form from density perturbations in the early Universe (Hawking 1971), and could provide an explanation for the non-baryonic dark matter. The masses of these objects depend on the exact time of formation. If primordial black holes formed during the quark-hadron phase transition at $\sim 10^{-6}$ s after the Big Bang, they could have masses in the right range ($\sim 0.1\, M_\odot$) to explain the MACHO detections (Sect. 1.9.2). At such high masses, black hole evaporation through Hawking radiation is not an issue, since only objects with original masses $< 5 \times 10^{11}$ kg would have had time to evaporate since the Big Bang. For objects below this mass, strong upper limits on the cosmic mass fraction of primordial black holes can however be imposed by the astrophysical consequences (production of observable gamma-rays and interference with BBNS) of the Hawking radiation (see Green & Liddle 1997, and references therein). The final phase of the evaporation process is however not well-constrained, and the formation of a Planck-mass relic – also a potential dark matter candidate – cannot be ruled out.

Preon stars

In scenarios in which quarks and leptons are composite particles build out of more elementary preons, very compact objects known as preon stars could possibly form (Hansson & Sandin 2004). These objects may have formed from density fluctuation in the early Universe (prior to BBNS) and are therefore not subject to the constraints on cosmic baryon density. These objects are predicted to have masses $\leq 10^{-3}\ M_{\odot}$ and to have radii ≤ 1 m, indicating an internal density much higher than that of a neutron star. They furthermore have no intrinsic luminosity (making the term "star" somewhat inappropriate). Hence, they are potential MACHO candidates.

Quark nuggets

Depending on the exact details of what happened during the transition from quarks to hadrons in the early Universe, primordial black holes may form, but so may quark nuggets (Witten 1984). The latter would consist of u, d and s quarks at a density larger than nuclear and may survive until the present time. They are expected to have masses in the range $\sim 10^{-18}$–$10^{-8} M_{\odot}$, and could possibly cluster to form more massive MACHOs (Banerjee et al. 2003). Since these objects formed prior to BBNS, they are not subject to constraints on the cosmic baryon density.

WIMPzillas

Superheavy particles in the 10^{21}–10^{28} eV mass range, also know as WIMPzillas, could have been produced in the early Universe and could represent the non-baryonic dark matter. These particles have primarily been evoked to explain the origin of ultra-high energy cosmic rays, as this could be attributed to the decay of particles of this mass. See Ziaeepour (2004) for an overview.

Matter in parallel branes

Brane cosmology (e.g. Khoury et al. 2001) has recently been suggested as an alternative to the standard Big Bang scenario for the origin of the observed Universe. In these models, the existence of extra spatial dimensions are assumed, so that the familiar Universe constitutes a three-dimensional membrane (3-brane) in a higher-dimensional space. Parallel universes in the form of other branes may also exist – separated from us along the additional dimension – the "bulk". While standard particles are confined to our brane, gravity can leak outside and enter other branes. Hence, what we observe as dark matter may simply be the gravitational influence of matter sitting in a parallel Universe. In principle, our brane may also be folded so that normal baryonic matter inside it could be responsible for the gravitational effects attributed to dark matter (see Arkani-Hamed et al. 2000, for a review).

Dark energy as dark matter

Several attempts have been made to find a common origin of the dark energy and dark matter phenomena. If these components of the Universe are related, this could explain the so-called coincidence (or "why now?") problem, i.e. why Ω_{M} and Ω_{Λ} happen to be of the same order at the current epoch. One of the models of this kind introduces a cosmic fluid with an equation of state given by:

$$p = -\frac{A}{\rho^{\alpha}}, \tag{1.19}$$

where A is a positive constant and α a constant in the range $0 \leq \alpha \leq 1$. This so-called generalized Chaplygin gas (e.g. Bento et al. 2004) can cluster and behave as CDM at early times while starting to behave as dark energy later on. Other scenarios which attempt to unify dark matter and dark energy include K-essence (Scherrer 2004) and WIMPzillas decaying into a scalar field acting as dark energy (Ziaeepour 2004).

1.9 Possible detections of dark matter

Although the nature of the dark matter remains elusive, a number of claimed detections of dark matter particles have been made. Here, two of these are described. It should however be noted that a number of other phenomena have also been attributed to dark matter, among them cosmic gamma-ray signals at 511 keV (Hooper & Wang 2004) and at >1 GeV (de Boer et al. 2004) due to to annihilation of WIMPs in the Milky Way system, cosmic positrons from annihilating WIMPs (e.g. Baltz et al. 2002), ultra high energy cosmic rays due to decaying dark matter (e.g. Ziaeepour 2004) and extreme scattering events in radio observations of quasars (Walker & Wardle 1998) due to an unknown population of gas clouds.

1.9.1 The annular modulation signal

If the dark matter halo of the Milky Way is in the form of WIMPs, the Earth should experience a WIMP “wind” of such particles as it moves through the halo due to its orbit around the Sun and the orbit of the Sun around the centre of the Galaxy. These WIMPs can in principle be detected through rare elastic scatterings off nuclei in a sufficiently sensitive detector on Earth. The scatterings may however easily drown in a background of other effects picked up by the detector. To evade this problem, one exploits the fact that the strength of the WIMP wind should display a seasonal variation with a well-defined period and phase. In June, the velocity of the Earth around the Sun is added to the velocity of the Sun around the Milky Way – giving maximal WIMP flux on Earth – whereas in December these two velocities act in the opposite directions – giving minimal WIMP flux. The situation is illustrated in Fig. 1.3. Because of this effect, the events induced by WIMPs should show an annular modulation, whereas the background should not. This annular modulation was detected by the DAMA set-up in an underground mine at Gran Sasso, Italy (Bernabei et al. 2000) at a claimed significance of an impressive 6.3σ.

Curiously, other similar set-ups, like EDELWEISS, Zeplin and CDMSII, have failed to confirm this signal, and claim to have excluded the DAMA detection (see e.g. Akerib et al. 2004). These other detectors are however not

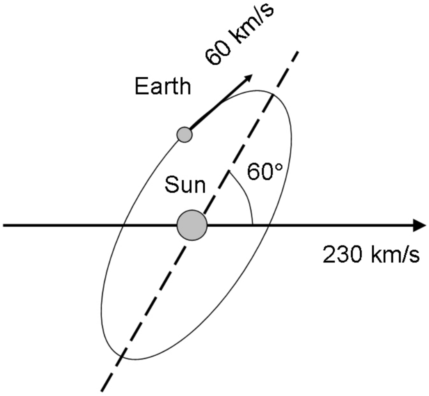

Figure 1.3: The orientation of the orbit of the Earth around the Sun compared to that of the Sun around the centre of the Milky Way. When the two orbital velocities add up (in June), the WIMP flux from the dark halo is maximized. When the Earth reaches the opposite position along its orbit (December), the flux is minimized.

identical to the one used by DAMA, and due to the large number of parameters involved in interpreting the result, a direct comparison is difficult. The possibility that certain kinds of WIMPs could be detectable in DAMA but evade detection in the other detectors cannot be ruled out (see Bernabei et al. 2005, for a discussion). While most investigations have assumed that the neutralino is responsible for the detected signal, mirror matter (Foot 2004b) has also been suggested as an alternative.

1.9.2 Microlensing events

If a compact objects passes through the line of sight to some distant light source (e.g. a star, supernova, quasar or gamma-ray burst), one may naively expect the compact object to obscure the light source, thereby decreasing the light that we receive from it. Provided that the foreground object is sufficiently massive and compact this will however not be the dominating effect. The compact object will instead locally curve spacetime and deflect rays of light passing close to it, thereby giving rise to a phenomenon somewhat similar to that of converging glass lens. Because of this gravitational lensing, light emitted from the light source can reach the observer along different paths, producing multiple images. The angle between these different images depends on the distances involved and the mass of the compact object. In certain situations, in particular in the case of a low-mass lens, the angle between the different images will be too small to be observed with current telescopes. In the case of a 1 $M_\odot$ lens, the image separation will for instance be on the order of microarcseconds. The only observable effect of such a *microlensing* event will therefore be a temporary enhancement of the light received from the background light

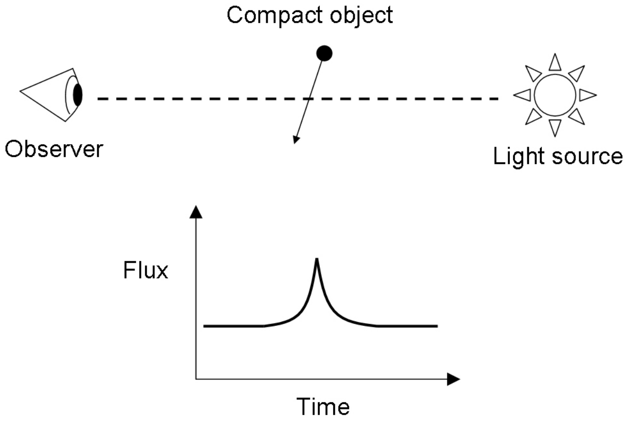

Figure 1.4: The microlensing light curve expected from a non-variable light source as a compact object crosses the line of sight.

source as the lens moves across the line of sight. By monitoring light sources with small or controllable intrinsic variations, MACHOs can be detected by the microlensing peaks that they produce in observed light curves (Fig. 1.4).

Even though the probability of seeing a microlensing event along the line of sight to a star in a nearby galaxy at a given time is minuscule, the chance of detecting MACHOs does become substantial if millions of stars are simultaneously monitored over a time span of a few years (Paczynski 1986). By monitoring $\sim 10^7$ stars in the Large and Small Magellanic Cloud (LMC and SMC, respectively), two satellite galaxies located inside the dark halo of the Milky Way, the MACHO and EROS/EROS2 projects have detected ≈ 20 such events (Alcock et al. 2000; Afonso et al. 2003). The analysis indicates that the objects responsible have masses of $\sim 10^{-1}\ M_{\odot}$ and may contribute around 20% to the mass of the dark halo.

As discussed in more detail in Sect. 2.4, microlensing events have also been detected in high-redshift galaxies along the line of sight to multiply-imaged quasars. In this case, the mass estimates are however more disparate, and the contribution of the responsible objects to the dark matter more unclear. Although it has been suggested that some of the MACHO/EROS detections may have been due to self-lensing (i.e. microlensing by stars *inside* the target galaxy rather than MACHOs in the dark halo of the Milky Way; Sahu 1994), background supernovae (Belokurov et al. 2004) or variable stars (Griest & Thomas 2004), these explanations cannot account for the high-redshift events. If some fraction of the dark matter is in the form of subsolar-mass MACHOs, there is in principle a very wide range of different baryonic and non-baryonic dark matter candidates which could be responsible, e.g. faint stars, gas clouds, primordial black holes, preon stars, clustered quark nuggets, mirror matter objects, axion aggregates (Membrado 1998) or objects in a parallel brane.

References

Afonso, C., Albert, J. N., Andersen, J., et al. 2003, A&A, 400, 951

Aguirre, A., Burgess, C. P., Friedland, A., & Nolte, D. 2001a, Classical and Quantum Gravity, 18, 223

Aguirre, A., Schaye, J., & Quataert, E. 2001b, ApJ, 561, 550

Ahn, K. & Shapiro, P. R. 2004, ArXiv Astrophysics e-prints, astro-ph/0412169

Akerib, D. S., Alvaro-Dean, J., Armel-Funkhouser, M. S., et al. 2004, Physical Review Letters, 93, 211301

Alcock, C., Allsman, R. A., Alves, D. R., et al. 2000, ApJ, 542, 281

Arkani-Hamed, N., Dimopoulos, S., Kaloper, N., & Dvali, G. 2000, Journal of High Energy Physics, 12, 10

Athanassoula, E. 2004, in IAU Symposium 220, 255

Athanassoula, E. & Sellwood, J. A. 1986, MNRAS, 221, 213

Babcock, H. W. 1939, Lick Observatory Bulletin, 19, 41

Badiei, S. & Holmlid, L. 2002, MNRAS, 333, 360

Bailin, J., Power, C., Gibson, B. K., & Steinmetz, M. 2005, ArXiv Astrophysics e-prints, astro-ph/0502231

Baltz, E. A., Edsjö, J., Freese, K., & Gondolo, P. 2002, Phys. Rev. D, 65, 063511

Banerjee, S., Bhattacharyya, A., Ghosh, S. K., et al. 2003, MNRAS, 340, 284

Banks, T., Dine, M., & Graesser, M. 2003, Phys. Rev. D, 68, 075011

Bekenstein, J. D. 2004, Phys. Rev. D, 70, 083509

Belokurov, V., Evans, N. W., & Le Du, Y. 2004, MNRAS, 352, 233

Bento, M. C., Bertolami, O., & Sen, A. A. 2004, Phys. Rev. D, 70, 083519

Bergström, L. 2000, Reports of Progress in Physics, 63, 793

Bernabei, R., Belli, P., Cappella, F., et al. 2005, ArXiv Astrophysics e-prints, astro-ph/0501412

Bernabei, R., Belli, P., Cerulli, R., et al. 2000, Physics Letters B, 480, 23

Bienaymé, O. 1999, A&A, 341, 86

Blumenthal, G. R., Faber, S. M., Primack, J. R., & Rees, M. J. 1984, Nature, 311, 517

Bode, P., Ostriker, J. P., & Turok, N. 2001, ApJ, 556, 93

Bosma, A. 2002, in Astronomical Society of the Pacific Conference Series 273, 223

Bullock, J. S., Dekel, A., Kolatt, T. S., et al. 2001, ApJ, 555, 240

Cardone, V. F. & Sereno, M. 2005, ArXiv Astrophysics e-prints, astro-ph/0501567

Carr, B. J. & Sakellariadou, M. 1999, ApJ, 516, 195

Cen, R. 2001, ApJ, 546, L77

Cen, R. & Ostriker, J. P. 1999, ApJ, 514, 1

Combes, F. 2004, in IAU Symposium 220, 219

Cowsik, R. & McClelland, J. 1973, ApJ, 180, 7

Cuillandre, J., Lequeux, J., Allen, R. J., Mellier, Y., & Bertin, E. 2001, ApJ, 554, 190

de Blok, W. J. G. & Bosma, A. 2002, A&A, 385, 816

de Boer, W., Herold, M., Sander, C., et al. 2004, ArXiv Astrophysics e-prints, astro-ph/0408272

Dong, S., Lin, D. N. C., & Murray, S. D. 2003, ApJ, 596, 930

D'Onghia, E. & Burkert, A. 2004, ApJ, 612, L13

Draine, B. T. 1998, ApJ, 509, L41

Einasto, J. 2004, ArXiv Astrophysics e-prints, astro-ph/0401341

Einasto, J., Kaasik, A., & Saar, E. 1974, Nature, 250, 309

Faber, S. M. & Lin, D. N. C. 1983, ApJ, 266, L17

Fabian, A. C., Thomas, P. A., White, R. E., & Fall, S. M. 1986, MNRAS, 221, 1049

Feng, J. L. 2005, Annals of Physics, 315, 2

Field, G. B. 1972, ARA&A, 10, 227

Foot, R. 2004a, ArXiv Astrophysics e-prints, astro-ph/0407623

Foot, R. 2004b, Modern Physics Letters A, 19, 1841

Fort, B. & Mellier, Y. 1994, A&A Rev., 5, 239

Freese, K. 2000, Phys. Rep., 333, 183

Fuchs, B. 2003, Ap&SS, 284, 719

Fukugita, M. 2004, in IAU Symposium 220, 227

Fukugita, M. & Peebles, P. J. E. 2004, ApJ, 616, 643

Green, A. M. & Liddle, A. R. 1997, Phys. Rev. D, 56, 6166

Griest, K. & Thomas, C. L. 2004, ArXiv Astrophysics e-prints, astro-ph/0412443

Hansson, J. & Sandin, F. 2004, ArXiv Astrophysics e-prints, astro-ph/0410417

Hawking, S. 1971, MNRAS, 152, 75

Hayashi, E., Navarro, J. F., Jenkins, A., et al. 2004, ArXiv Astrophysics e-prints, astro-ph/0408132

He, P., Feng, L., & Fang, L. 2005, ArXiv Astrophysics e-prints, astro-ph/0501404

Hoekstra, H., Yee, H. K. C., & Gladders, M. D. 2004, in IAU Symposium 220, 439

Holmlid, L. 2000, A&A, 358, 276

Hooper, D. & Wang, L. 2004, Phys. Rev. D, 70, 063506

Hu, W., Barkana, R., & Gruzinov, A. 2000, Physical Review Letters, 85, 1158

Hubble, E. 1929, Proceedings of the National Academy of Science, 15, 168

Ibata, R., Lewis, G. F., Irwin, M., Totten, E., & Quinn, T. 2001, ApJ, 551, 294

Jimenez, R., Heavens, A. F., Hawkins, M. R. S., & Padoan, P. 1997, MNRAS, 292, L5

Jimenez, R., Verde, L., & Oh, S. P. 2003, MNRAS, 339, 243

Jing, Y. P. & Suto, Y. 2002, ApJ, 574, 538

Kahn, F. D. & Woltjer, L. 1959, ApJ, 130, 705

Kalberla, P. M. W. 2003, ApJ, 588, 805

Kaplinghat, M., Knox, L., & Turner, M. S. 2000, Physical Review Letters, 85, 3335

Kazantzidis, S., Kravtsov, A. V., Zentner, A. R., et al. 2004, ApJ, 611, L73

Khoury, J., Ovrut, B. A., Steinhardt, P. J., & Turok, N. 2001, Phys. Rev. D, 64, 123522

Kuijken, K. & Gilmore, G. 1989, MNRAS, 239, 571

Lynds, R. & Petrosian, V. 1986, BAAS, 18, 1014

Müller, C. M. 2005, Phys. Rev. D, 71, 047302

Maller, A. H. & Dekel, A. 2002, MNRAS, 335, 487

Mao, S. 2004, in IAU Symposium 220, 85

Masset, F. S. & Bureau, M. 2003, ApJ, 586, 152

Mateo, M. L. 1998, ARA&A, 36, 435

McGaugh, S. S. 2004, ApJ, 611, 26

Membrado, M. 1998, MNRAS, 296, 21

Milgrom, M. 1983, ApJ, 270, 365

Minchin, R., Davies, J., Disney, M., et al. 2005, ApJ, 622, L21

Moore, B., Ghigna, S., Governato, F., et al. 1999, ApJ, 524, L19

Napier, W. M. & Guthrie, B. N. G. 1975, MNRAS, 170, 7

Navarro, J. F., Frenk, C. S., & White, S. D. M. 1996, ApJ, 462, 563

Navarro, J. F., Frenk, C. S., & White, S. D. M. 1997, ApJ, 490, 493

Navarro, J. F., Hayashi, E., Power, C., et al. 2004, MNRAS, 349, 1039

Nicastro, F., Mathur, S., Elvis, M., et al. 2005, Nature, 433, 495

Olling, R. P. 1996, AJ, 112, 481

Oort, J. H. 1932, Bull. Astron. Inst. Netherlands, 6, 249

Oort, J. H. 1960, Bull. Astron. Inst. Netherlands, 15, 45

Ostriker, J. P. & Peebles, P. J. E. 1973, ApJ, 186, 467

Ostriker, J. P., Peebles, P. J. E., & Yahil, A. 1974, ApJ, 193, L1

Paczynski, B. 1986, ApJ, 304, 1

Padmanabhan, T. 2003, Phys. Rep., 380, 235

Peebles, P. J. & Ratra, B. 2003, Reviews of Modern Physics, 75, 559

Peebles, P. J. E. 1982, ApJ, 263, L1

Pfenniger, D. & Combes, F. 1994, A&A, 285, 94

Pfenniger, D., Combes, F., & Martinet, L. 1994, A&A, 285, 79

Power, C., Navarro, J. F., Jenkins, A., et al. 2003, MNRAS, 338, 14

Primack, J. R. 2001, ArXiv Astrophysics e-prints, astro-ph/0112336

Primack, J. R. 2004, in IAU Symposium 220, 467

Primack, P. J. E. 1982, ApJ, 263, L1

Rauch, M. 1998, ARA&A, 36, 267

Revaz, Y. & Pfenniger, D. 2004, A&A, 425, 67

Riess, A. G. 2000, PASP, 112, 1284

Roberts, M. S. & Whitehurst, R. N. 1975, ApJ, 201, 327

Rubin, V. C. & Ford, W. K. J. 1970, ApJ, 159, 379

Sackett, P. D. 1999, in Astronomical Society of the Pacific Conference Series 182, 393

Sahu, K. C. 1994, PASP, 106, 942

Sanders, R. H. 2003, MNRAS, 342, 901

Sanders, R. H. & McGaugh, S. S. 2002, ARA&A, 40, 263

Scherrer, R. J. 2004, Physical Review Letters, 93, 011301

Sciama, D. W. 1990, ApJ, 364, 549

Simon, J. D., Robishaw, T., & Blitz, L. 2003, ArXiv Astrophysics e-prints, astro-ph/0310192

Smith, S. 1936, ApJ, 83, 23

Spekkens, K. & Giovanelli, R. 2005, ArXiv Astrophysics e-prints, astro-ph/0502166

Spergel, D. N. & Steinhardt, P. J. 2000, Physical Review Letters, 84, 3760

Spergel, D. N., Verde, L., Peiris, H. V., et al. 2003, ApJS, 148, 175

Stewart, G. C., Fabian, A. C., Nulsen, P. E. J., & Canizares, C. R. 1984, ApJ, 278, 536

Swaters, R. A., Madore, B. F., van den Bosch, F. C., & Balcells, M. 2003, ApJ, 583, 732

Tegmark, M., Strauss, M. A., Blanton, M. R., et al. 2004, Phys. Rev. D, 69, 103501

Thorstensen, J. R. & Partridge, R. B. 1975, ApJ, 200, 527

Trentham, N., Moeller, O., & Ramirez-Ruiz, E. 2000, ArXiv Astrophysics e-prints, astro-ph/0010545

Tubbs, A. D. & Sanders, R. H. 1979, ApJ, 230, 736

Valle, J. W. F. 2004, ArXiv High Energy Physics - Phenomenology e-prints, hep-ph/0410103

van den Bosch, F. C., Tormen, G., & Giocoli, C. 2004, ArXiv Astrophysics e-prints, astro-ph/0409201

van der Kruit, P. C. & Shostak, G. S. 1984, A&A, 134, 258

Verde, L., Oh, S. P., & Jimenez, R. 2002, MNRAS, 336, 541

Walker, M., Mori, M., & Ohishi, M. 2003, ApJ, 589, 810

Walker, M. & Wardle, M. 1998, ApJ, 498, L125

Walker, M. & Wardle, M. 1999, Publications of the Astronomical Society of Australia, 16, 262

Walsh, D., Carswell, R. F., & Weymann, R. J. 1979, Nature, 279, 381

Weinberg, D. H., Miralda-Escude, J., Hernquist, L., & Katz, N. 1997, ApJ, 490, 564

Witten, E. 1984, Phys. Rev. D, 30, 272

Zentner, A. R. & Bullock, J. S. 2002, Phys. Rev. D, 66, 043003

Ziaeepour, H. 2004, ArXiv Astrophysics e-prints, astro-ph/0406079

Zwicky, F. 1933, Helvetica Phys. Acta, 6, 110

Zwicky, F. 1937, ApJ, 86, 217