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Quasars and Low Surface Brightness Galaxies as Probes of Dark Matter

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Abstract
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Most of the matter in the Universe appears to be in some form which does not emit or absorb light. While evidence for the existence of this dark matter has accumulated over the last seventy years, its nature remains elusive. In this thesis, quasars and low surface brightness galaxies (LSBGs) are used to investigate the properties of the dark matter.

Quasars are extremely bright light sources which can be seen over vast distances. These cosmic beacons may be used to constrain dark matter in the form of low-mass, compact objects along the line of sight, as such objects are expected to induce brightness fluctuations in quasars through gravitational microlensing effects. Using a numerical microlensing model, we demonstrate that the uncertainty in the typical size of the optical continuum-emitting region in quasars represents the main obstacle in this procedure. We also show that, contrary to claims in the literature, microlensing fails to explain the observed long-term optical variability of quasars. Here, quasar distances are inferred from their redshifts, which are assumed to stem from the expansion of the Universe. Some astronomers do however defend the view that quasar redshifts could have a different origin. A number of potential methods for falsifying claims of such non-cosmological redshifts are proposed.

As the ratio of dark to luminous matter is known to be unusually high in LSBGs, these objects have become the prime targets for probing dark matter halos around galaxies. Here, we use spectral evolutionary models to constrain the properties of the stellar populations in a class of unusually blue LSBGs. Using rotation curve data obtained at the ESO Very Large Telescope, we also investigate the density profiles of their dark halos. We find our measurements to be inconsistent with the predictions of the currently favoured cold dark matter scenario.

Keywords: Cosmology: dark matter, gravitational lensing, quasars: general, quasars: redshift, galaxies: halos, galaxies: formation, galaxies: stellar content

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Nu är det natt över jorden.
Darrande stjärna, gläns.
Världarna vandra så fjärran.
Mörkret är utan gräns.

Blomberg (1920)

List of Papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.

I   Zackrisson, E., & Bergvall. N.:
"Constraining the cosmological density of compact objects with the long-term variability of quasars"
Astronomy & Astrophysics 399, 23 (2003)

II   Zackrisson, E., Bergvall, N., Marquart, T., & Helbig, P.:
"Can microlensing explain the optical long-term variability of quasars?"
Astronomy & Astrophysics 408, 17 (2003)

III   Zackrisson, E.:
"On quasar host galaxies as tests of non-cosmological redshifts"
Monthly Notices of the Royal Astronomical Society, in press (2005)

IV   Zackrisson, E., Bergvall, N., & Östlin, G.:
"The stellar populations of the bluest low surface brightness galaxies"
Astronomy & Astrophysics, in press (2005)

V   Zackrisson, E., Bergvall, N., Marquart, T., & Östlin, G:
"The dark matter halos of the bluest low surface brightness galaxies"
Astronomy & Astrophysics, to be submitted (2005)

Refereed papers not included in the thesis:

1. Östlin, G, Cummings, R. J., Amram, P., Bergvall, N., Kunth, D., Marquez, I., Masegosa, J., & Zackrisson, E.:
   "Stellar dynamics of blue compact galaxies. I. Decoupled star-gas kinematics in ESO 400-G43"
   Astronomy & Astrophysics 419, L43 (2004)

2. Östlin, G, Zackrisson, E., Bergvall, N., & Rönnback, J.:
   "The temporal and spatial evolution of the starburst in ESO 338-IG04 as probed by its star clusters"
   Astronomy & Astrophysics 408, 887 (2003)

3. Zackrisson, E., Bergvall, N., Olofsson, K., & Siebert, A.:
   "A model of spectral galaxy evolution including the effects of nebular emission"
   Astronomy & Astrophysics 375, 814 (2001)

4. Bergvall, N., Östlin, G., Masegosa, J., & Zackrisson, E.:
   "Starburst dwarfs – fueling and morphological evolution"
   Astrophysics & Space Science 269, 625 (1999)

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 the 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:

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

where a is the cosmic scale factor (which can be set to $a_{\mathrm{obs}} = 1$ 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:

$$\frac{\dot{a}^2 + kc^2}{a^2} = \frac{8\pi G\rho_{\mathrm{tot}}}{3}, \tag{1.2}$$

and

$$\frac{2\ddot{a}}{a} + \frac{\dot{a}^2 + kc^2}{a^2} = -\frac{8\pi G p_{\mathrm{tot}}}{c^2}, \tag{1.3}$$

where ρ_{tot} represents the total mass density of the Universe, p_{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:

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

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:

$$p = w\rho c^2, \tag{1.5}$$

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:

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

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:

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

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:

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

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

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

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

The most important contributions to the density $\rho_{\rm tot}$ of the Universe are often assumed be:

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

where $\rho_{\rm M}$ represents the density contribution from non-relativistic matter and $\rho_{\rm rad}$ 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 $\rho_\Lambda =$ 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 Ein-

[1] This was at a time before the discovery of the cosmic expansion (Hubble 1929). It was later also 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

stein'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 consistent 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 contributions from radiation and relativistic matter), where $\Omega_{\text{M}} \approx 0.3$ 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 $\Omega_{\text{lum}} \approx 0.0051$ 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 Ω_{lum} is $\Omega_{\text{stars}} \approx 0.0027$ and the contribution from gas (HI, HeI, H_2 and X-ray gas) $\Omega_{\text{gas}} \approx 0.0024$[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 Ω_{bar} can be derived. Investigations of this type currently indicate $\Omega_{\text{bar}} \approx 0.045$ (e.g. Spergel et al. 2003). Since $\Omega_{\text{M}} \approx 0.3$, 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

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.

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

$\Omega_{\rm lum} < \Omega_{\rm bar}$ 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 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 $\Omega_M \approx 0.3$, $\Omega_\Lambda \approx 0.7$), 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.

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 painted 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.

[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.

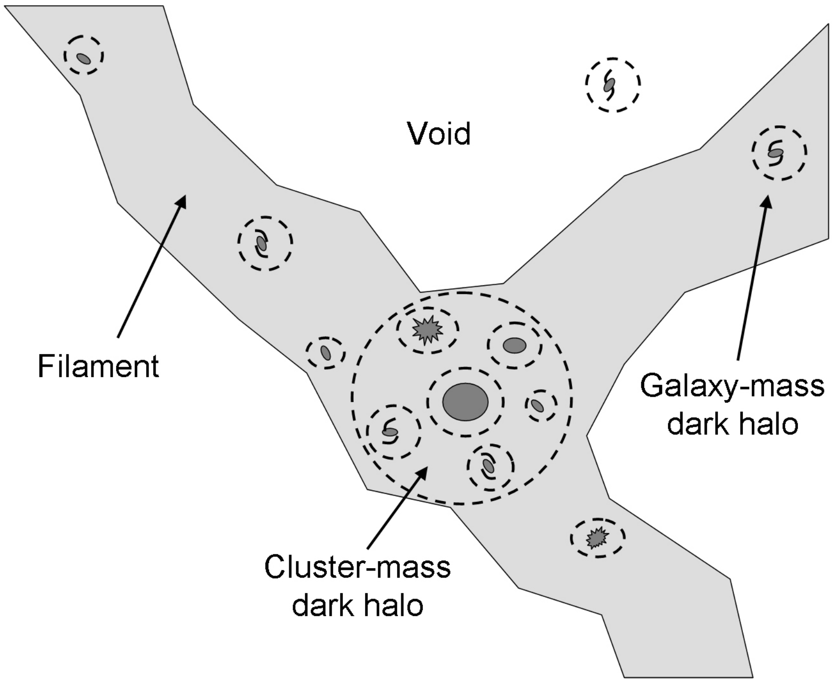

Figure 1.1: Schematic illustration of the distribution of galaxies and dark matter on large scales. A string of galaxy-mass dark halos (containing galaxies of varying morphological type) are located in medium-density filaments leading into a larger halo of galaxy-cluster mass. At the centre of the cluster, 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 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 are also an option (Revaz & Pfenniger 2004).

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:

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

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:

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

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:

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

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:

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

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:

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

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

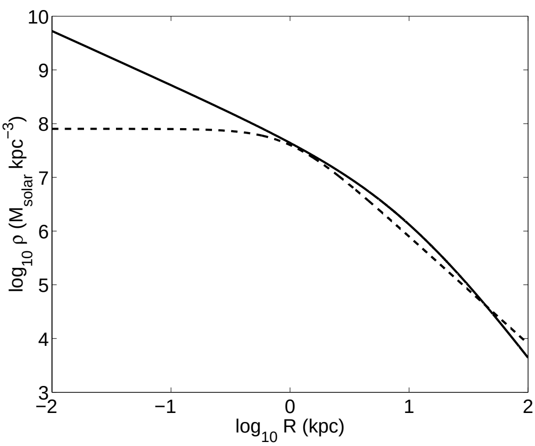

Figure 1.2: The density profile of an NFW halo with $R_S = 10$ kpc (solid) compared to that of an pseudo-isothermal sphere with $R_C = 1$ kpc (dashed). The total mass of both halos inside a radius of 100 kpc is 10^{11} $M_\odot$. While the density of the NFW halo continues to rise within the central 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 the Milky Way (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 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

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

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 far out into the halo. 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 ($\nu_{\rm e}$, 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 reflectance symmetry (parity) and time reflectance 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

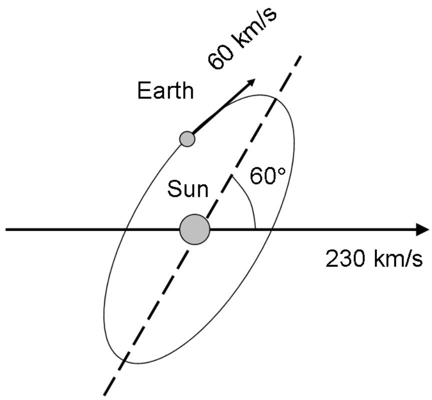

Figure 1.3: The orientation of the orbit of the Earth around the Sun compared to that of the Sun around the centre of the Milky Way. When the two orbital velocities add up (in June), the WIMP flux from the dark halo is maximized. When the Earth reaches the opposite position along its orbit (December),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

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 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 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

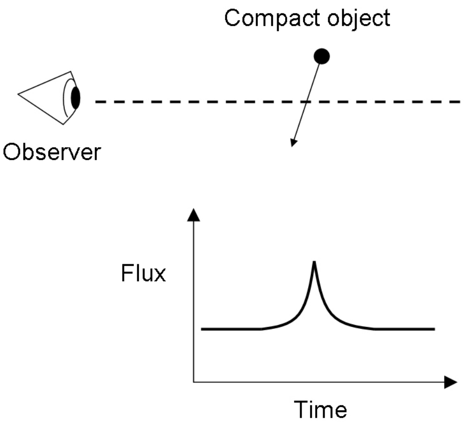

Figure 1.4: The microlensing light curve expected from a non-variable light source as a compact object crosses the line of sight.

dark matter candidates which could be responsible, e.g. faint stars, gas clouds, primordial black holes, preon stars, clustered quark nuggets, mirror matter objects, objects in a parallel brane or axion aggregates (Membrado 1998).

2. Quasars as probes of dark matter

2.1 Quasars

The discovery of the first quasar, 3C 273, is usually attributed to Schmidt (1963), although radio astronmers had been mystified by the same objects since the late 1950s (to them known as "radio stars", due to the small angular sizes of these radio sources). Although quasars are characterized by non-extended, star-like appearances in the optical, their spectra display high redshifts, indicating that they are not local stars but instead extremely luminous objects located very far away in the Universe. Originally, a distinction was made between objects which were detected at radio wavelengths ("Quasi-stellar radio sources", or quasars for short) and those only seen in the optical ("Quasi-Stellar Objects", or QSOs). Today, both the radio-loud and radio-quiet objects are normally referred to as quasars. With the advent of large extragalactic surveys (covering millions of objects) in the late 1990s, like 2dF and the Sloan Digital Sky Survey (SDSS), the number of known quasars has rapidly increased. Around 1990, the number of known quasars was ~ 5000. The 3rd SDSS data release (Abazajian et al. 2004) alone contains spectra of ~ 50000 quasars.

Quasars represent the most energetic of the non-transient astronomical objects, having total luminosities in the range $\sim 10^{45}$–10^{48} erg/s. By comparison, the total luminosity of the Milky Way is estimated to be $\sim 10^{44}$ erg/s. In the standard model, quasars represent but one type of objects collectively known as Active Galactic Nuclei (AGN). As the name implies, AGN are phenomena associated with the central regions of certain galaxies. Most, if not all galaxies, are believed to harbour an object known as a supermassive black hole at their centre. In the Milky Way, the mass of this objects is around $M_{\mathrm{SMBH}} \approx 4 \times 10^6\ M_\odot$ (Schödel et al. 2002). In other galaxies, estimates indicate masses as high as a few times $10^9\ M_\odot$ (e.g. Kormendy 2001; McLure & Dunlop 2001). Due to the powerful gravitational field of these SMBHs, surrounding matter is being pulled inside. For some reason, the details of which are still not entirely clear, certain galaxies are so efficient in "feeding the monster", that an AGN is created. In AGN, the high luminosities are produced as gravitational energy of the infalling material is transformed into radiation due to viscous dissipation (friction) in a rotating accretion disk surrounding the SMBH. Close to the SMBH, matter is funneled into two jets, in which matter is being ejected outwards at relativistic velocities. The geometry of this phenomenon is illustrated in Fig. 2.1. The observed properties and classification of a particular AGN are believed to largely depend on the angle at which we happen to see this structure. In the case of quasars, the viewing angle is believed to be $\leq 45°$.

The optical spectrum of a quasar displays some very broad emission lines, believed to originate in a structure (the broad-line region, BLR) substantially larger than that responsible for the continuum radiation. The line widths reflect the large velocities induced by the gravitational influence of the SMBH, and can therefore be used to estimate the black hole mass if the characteristic radius of the BLR is known. The BLR size is measured through a technique known as reverberation mapping, in which variations in luminosity of both continuum and emission lines are carefully monitored for a few months. On these time scales, light variations in the quasar continuum are usually followed by corresponding variations in the line emission after a certain time lag, reflecting the light travel time between the accretion disk and the site at which the lines are produced. By measuring this time delay, a rough estimate of the BLR radius can be calculated. Reverberation mapping, as well as other arguments, suggest that the masses of SMBHs in quasars typically are $\geq 10^8\ M_\odot$ (e.g. Kaspi et al. 2000; McLure & Dunlop 2001; Dunlop et al. 2003).

In theory, the SMBH mass imposes an upper limit on the quasar luminosity. Assuming spherical accretion onto the SMBH, the luminosity produced by the AGN cannot exceed the Eddington limit, L_E, at which the outward radiation pressure balances the inward pull of gravity:

$$L_\mathrm{E} = 1.3 \times 10^{46} \frac{M_\mathrm{SMBH}}{10^8 M_\odot}\ \mathrm{erg/s}. \tag{2.1}$$

In real life, super-Eddington luminosities are however sometimes observed, and a number of more sophisticated accretion models have been suggested to explain this phenomenon (see e.g. Collin et al. 2002).

For reasons which are not quite clear, quasar activity was much more common in the early universe, peaking at a redshift of $z \approx 2$–3, when the comoving space density of quasars was a factor of ~ 1000 higher than today. The likely reason for this is that the mechanism for providing gas supply to the AGN has become less efficient over time.

In dark matter research, quasars are mainly useful because they represent non-transient beacons which can be observed at large distances. Because of this property, the light received at Earth from quasar contains information on the matter distribution along the line of sight through a substantial fraction of the observable Universe. In the dark matter context, the most important mechanisms affecting the observed properties of quasars are gaseous absorption and gravitational lensing.

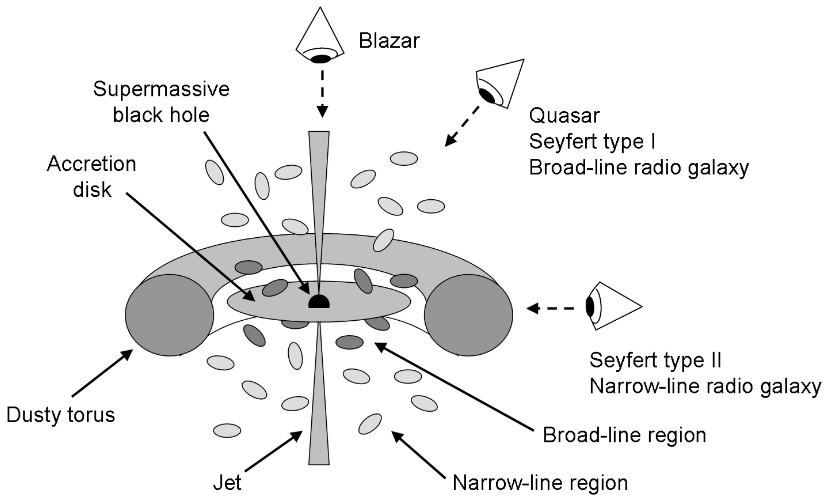

Figure 2.1: The geometry of the AGN assumed in unified models where the classification of the central light source mainly depends on the viewing angle. The approximate viewing angles of certain types of AGN have been indicated, although many subgroups have been omitted. The individual components of the central engine are not plotted to scale.

2.2 Quasar absorption features

The quasar spectrum displays a wealth of absorption features produced in neutral gas clouds of different densities at various distances along the line of sight. These are usually labeled by the way they manifest themselves in the spectrum. Of particular interest for dark matter is the Lyman-α forest – a large number of narrow lines observed on the blueward side of the redshifted Lyman-α emission line ($\lambda = 1216$ Å in the rest frame). These absorption features arise in the low-density gas of the intergalactic medium and reflect the large scale structure (filaments, walls and voids) of the Universe. For this reason, the observed distribution of Lyman-α forest lines can be used to infer cosmological parameters, and appears to be reasonably consistent with the currently favoured ΛCDM scenario (e.g. Weinberg et al. 2003). As discussed in section 1.3, observations of the Lyman-α forest also indicate that most of the baryons of the Universe are likely to be gaseous at a redshift of $z \approx 2$–3, limiting the baryonic dark matter problem to the form taken by the missing baryons in the local Universe. Other less common absorption features, like the Damped Lyman-α clouds and the Lyman-limit systems, are usually attributed to dense gas inside or in close proximity of galaxies.

2.3 Quasar macrolensing

If a very massive object, like a galaxy or a galaxy cluster, happens to be located close to the line of sight, then light from a quasar may reach us on slightly different paths, forming multiple images (or – in the case of perfect alignment – a ring) of a single quasar. This phenomenon is often referred to as macrolensing (when the angle between the images is $\sim 1''$, as opposed to microlensing – when the angle is $\sim 10^{-6}\,''$ and the deflector is an object of much lower mass). Since close alignments of this type are very rare, only about 1 out of 500 quasars displays multiple images. To this date, more than a hundred candidates for such quasars have been identified. Both the number of images seen, their positions and flux ratios can be used to constrain the mass distribution within the deflectors. So far, the density profiles and the amount of substructure predicted for CDM halos have been problematic to reconcile with the observed properties of multiply-imaged quasars (e.g. Keeton 2001; Metcalf 2005).

2.4 Quasar microlensing

Due to their small sizes and large distances from us, the light that we receive from quasars may not only be affected by gravitational macrolensing, but also by microlensing. Soon after the first discovery of 0957+561, the first multiply-imaged quasar (Walsh et al. 1979), it was predicted that microlensing could produce temporal variations in the different images (e.g. Chang & Refsdal 1979; Gott 1981). This would be distinguishable from intrinsic quasar variability, since the latter variations would be seen in all images (albeit with a certain time delay, due to the different length of the light path), whereas microlensing-induced variations would be uncorrelated between the different images. The first such microlensing variations, supposedly produced by low-mass stars or other compact object in the foreground galaxy responsible for the macrolensing effects, were detected by Irwin et al. (1989) in the gravitationally lensed quasar 2237+0305, known as the "Einstein cross" because of its four symmetrical images. Since that time, microlensing events have been detected in several other multipy-imaged quasars as well. Because of the need to measure the time delay (unless it is very short) of the systems used, not all multiply-imaged quasars hoever are equally suitable for microlensing studies of this type, as this could require very long monitoring programmes.

The nature of the compact objects detected in multipy-imaged quasars is still not clear. Whereas some (e.g. Wyithe et al. 2000a; Refsdal et al. 2000) have detected objects in the same mass range (~ 0.01–$0.1\ M_\odot$) as those found by the MACHO/EROS projects in the halo of the Milky Way, others (Schild 1996) claim the detection of Earth-mass objects ($\sim 10^{-5}\ M_\odot$).

2.5 Microlensing as a mechanism for the optical long-term variability of quasars

Quasars are highly variable light sources, displaying substantial luminosity variations on time scales from weeks[1] to decades. Due to the finite speed of light, the shortest timescale sets an upper limit to the size of the region in which the radiation is produced. Curiously, the rapid variability of quasars implies that the region responsible for their huge luminosities cannot be more than one light week ($\sim 10^{14}$ m) across, which is only ~ 40 times larger than the Solar system. Compared to the size of a typical galaxy ($\sim 10^{21}$ m), this is a very small region indeed, highlighting the very extreme conditions prevalent around the central SMBH.

The correlation between continuum and line emission variations on short time scales (less than a year), as well as our ability to observe time lags in multiply-imaged systems, strongly suggest that these variations are due to intrinsic variations in the quasar AGN. This is not necessarily the case for the variability on timescales of a few years. For the optical long-term variability, three different models have been suggested. The most mainstream one is that quasar variability is caused by accretion disk instabilities. In this case, radial avalanches of matter occur stochastically within the disk and cause small outbursts of increased luminosity by converting potential energy into radiation (Mineshige et al. 1994). In the more speculative starburst model, the quasar is assumed not to be powered by accretion onto a SMBH, but instead by a very compact starburst (Terlevich et al. 1992; Aretxaga et al. 1997). The long-term variations could in this case be caused by a superposition of many supernovae. This scenario does however fail for the most luminous quasars, as the number of supernovae required in these cases is so high that only very small brightness variations would be seen. There is finally the possibility that an extrinsic mechanism, like gravitational microlensing, could be responsible (see e.g. early suggestions by Gott 1981; Canizares 1982; Schneider & Weiss 1987) for the variations seen in quasars (i.e. not only in multiply-imaged ones).

In 1993, M. R. S. Hawkins proposed – based on a sample of approximately 300 quasars monitored regularly in the optical for 17 years – that the long-term variations in the light curves of these objects were caused by microlensing by a population of $\sim 10^{-3}\ M_{\odot}$ objects along the line of sight (Hawkins 1993). Since essentially every quasar studied displays this type of long-term variability, this interpretation implies that such Jupiter-mass microlenses must contribute substantially to the dark matter of the Universe.

Apart from contributing to the solution of the dark matter problem, this

[1] Small intranight variations are sometimes also observed, usually attributed to a subdominant relativistic jet (Stalin et al. 2005) similar to that responsible for the very fast variability in blazars.

scenario also has many other attractive features. In fact, microlensing is the only mechanism proposed which, at least qualitatively, appears to generically explain the achromaticity, statistical symmetry and lack of cosmological time dilation observed in the long-term optical brightness variations of quasars.

2.5.1 Achromaticity

On long time scales, quasar light curves are known to be nearly achromatic in the optical (Hawkins 1996, 2003). Intrinsic mechanisms for brightness variations, like supernovae and accretion disk instabilities, do not typically predict this behaviour, but under certain circumstances, microlensing does. In general, the magnification caused by gravitational lensing does not depend on the wavelength of light. In this respect, a gravitational lens behaves fundamentally different from a glass lens, for which the bending angle does indeed depend on the wavelength – this is the principle behind an optical prism. In the case of a point source, or a light source unresolved by the lens, microlensing therefore predicts achromatic variations. Once the part of the light source responsible for the observed continuum becomes resolved by the microlens, the situation does however become more complicated.

Due to the expansion of the Universe, distances in cosmology may be defined in a variety of ways (e.g. Kayser et al. 1997). In gravitational lensing, it is usually the angular size distances which are relevant, which measure distances to objects of linear size l by the angle θ that they subtend in the sky. For small angles, the angular size distance between two points x and y becomes:

$$D_{\mathrm{xy}} = \frac{l}{\theta}. \tag{2.2}$$

In the special case of a spatially flat ($k = 0$; $\Omega_{\mathrm{M}} + \Omega_{\Lambda} = 1$) universe with a cosmological constant Λ and matter distributed homogeneously, the angular size distance can be expressed as (see Kayser et al. 1997, for more general solutions):

$$D_{xy} = \frac{c}{(1+z_y)H_0} \int_{z_x}^{z_y} \frac{dz}{\sqrt{\Omega_{\mathrm{M}}(1+z)^3 - (\Omega_{\mathrm{M}}+\Omega_{\Lambda}-1)(1+z)^2 + \Omega_{\Lambda}}}, \tag{2.3}$$

where z_x and z_y represent the redshifts of the points x and y.

By definition, the Einstein radius of a lens is

$$R_{\mathrm{E}} = \sqrt{\frac{4GMD_{\mathrm{d}}D_{\mathrm{ds}}}{c^2 D_{\mathrm{s}}}}. \tag{2.4}$$

This represents the radius inside which most of the magnification takes place. Following the convention of the gravitational lensing literature, D_{d} here represents the distance from the observer to the lens, D_{s} the distance from the observer to the source and D_{ds} the distance from the lens to the source.

The projected source radius, R_S at the distance of the lens is on the other hand given by:

$$R_S = \frac{l_S D_d}{D_s}, \quad (2.5)$$

where l_S represents the true source size.

As long as $R_S < R_E$, the source can be considered small, and variations will be achromatic. When this condition is no longer met, parts of the source may be subject to substantial magnification whereas others are largely unaffected. In the case of a source of uniform colour, i.e. when the shape of its luminosity profile is independent of wavelength, achromatic variations will still be produced. This situation is however not considered realistic for quasars. In quasars, the UV and optical continua are believed to originate in an accretion disk with a radial temperature gradient such that the inner region is hotter (bluer) than the outer part. Since the magnification increases with decreasing source size, a higher magnification is expected at shorter wavelengths. The exact behaviour depends on the detailed source profile and its colour gradient. For the quasars where the observed variations are not perfectly achromatic, the variations at bluer passbands typically display sharper features than in the red. This behaviour is consistent with microlensing (since a smaller source in the blue implies a shorter microlensing time scale and a higher magnification), but possibly accretion disk instabilities as well (see Hawkins 2003, and references therein).

2.5.2 Statistical symmetry

In the case where a substantial fraction, or even all, of the dark matter is in the form of low-mass compact objects, the optical depth to lensing becomes large for a high-redshift light source, and several microlenses may simultaneously contribute to the light curve of any given quasar. Instead of seeing separate microlensing peaks of the type shown in Fig. 1.4, one would instead expect stochastic fluctuations of the type illustrated in Fig. 2.2, which more resemble the brightness fluctuations actually observed in optical quasar light curves. While the magnification caused by a single microlens is time-symmetric (Fig. 1.4), the light curve of a quasar affected by microlensing at high optical depth (Fig. 2.2) will in general not appear to be. There will however still be statistical symmetry, in the sense that the distribution of positive and negative magnitude changes should be identical. According to Hawkins (1996, 2002), the observed long-term optical variations do indeed obey this symmetry criterion. Neither the starburst nor accretion disk scenarios generically predict this behaviour (Kawaguchi et al. 1998). The starburst-induced variations are characterized by fast rise and slow decline (as in the light curve of a single supernova), whereas for accretion disk instabilities, a slow rise and a fast decline is expected. These asymmetries are admittedly mainly expected on time scales smaller than one year, and at longer time scales, both scenarios could produce largely symmetric variations for certain model parameter values.

2.5.3 The lack of cosmological time dilation

Perhaps the best argument in favour of microlensing-induced variations (or some other extrinsic variability mechanism) is the observed lack of cosmological time dilation in quasar light curves. Due to the expansion of the Universe, time signals emitted from objects at redshift z are stretched by a factor of $(1+z)$. For intrinsically variable light sources, one therefore expects the time scale of the variations to be proportional to this factor. This effect has been established in the light curves of supernovae (e.g. Riess et al. 1997), and has been claimed for gamma-ray bursts (Deng & Schaefer 1998). The characteristic time scales of the variations seen in quasar light curves do, on the other hand, not appear to be dependent on redshift (Hawkins 2001). This is consistent with the conjecture that the variations are extrinsic to the quasars, i.e. produced somewhere along the line of sight. Although microlensing-induced variations are also subject to cosmological time dilation, the redshift of interest in this case is not the redshift of the quasar, but that of the microlens. Since each quasar may be affected by compact objects at several different redshifts along the line of sight, no strong $(1+z)$ signal is therefore expected in a statistical analysis of the characteristic variation time scales. The possibility that the lack of cosmological time dilation in the quasar light curves is due to wavelength-dependent variation time scales for some intrinsic mechanism has been ruled out by comparing light curves obtained in different filters (Hawkins & Taylor 1997; Hawkins 2001). In principle, it is conceivable that the redshift evolution of some intrinsic mechanism for variability could cancel out the time dilation effect, i.e. by giving variations whose time scales decrease exactly by a factor of $(1+z)$. This would however require fine-tuning, and no such mechanism has yet been proposed.

2.6 Microlensing as a mechanism for quasar variability at other wavelengths

In summary, there is a reasonably compelling case for microlensing-induced quasar variability in the UV–optical[2] wavelength range. At shorter wave-

[2]Since the UV rest frame will be redshifted into the optical region of the observer for a high-redshift object.

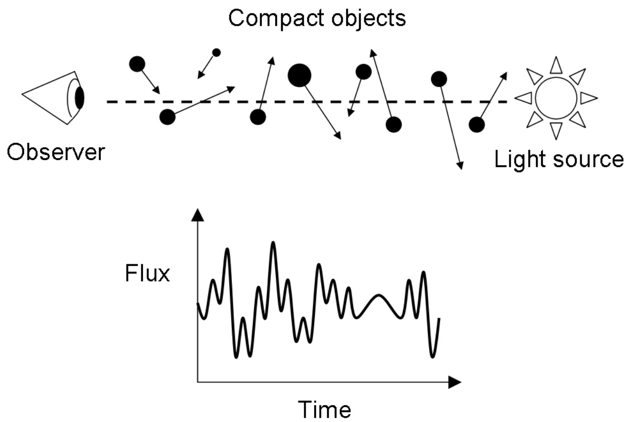

Figure 2.2: The microlensing light curve expected from a non-variable light source as several compact objects cross the line of sight more or less simultaneously at different distances from the observer.

lengths, where the region responsible for emission may be even smaller than in the UV–optical, microlensing could in principle cause even larger fluctuations. In X-rays, quasars are known to fluctuate violently on time scales from hours to years, and suggestions have been made that the redshift dependence of the variations could be explained by microlensing (e.g. Zakharov et al. 2004). At longer wavelengths, the size of the region responsible for the radiation observed is generally expected to be too large for microlensing to be efficient. This is confirmed by constraints on the mid-IR source size for the multiply-imaged quasar 2237+0305 (Wyithe et al. 2002). However, in the special case of a relativistic jet close to the line of sight, substantial short-term microlensing variability in the radio domain is possible and has been convincingly detected in at least one multiply-imaged system (Koopmans & de Bruyn 2000). The possibility that similar extrinsic variations could also be caused by scattering of radio waves by the ionized component of the Galactic interstellar medium does however complicate the extension of this result to radio quasars which are not multiply-imaged.

2.7 Quasars as probes of dark matter in the form of compact objects

As discussed in section 1.9.2, searches for microlensing effect towards local galaxies like LMC and SMC have possibly revealed a population of $\sim 0.1\ M_{\odot}$ MACHOs. In addition to these intriguing results, surveys of this type can also impose strong upper limits on the contribution to halo dark matter by compact objects in the mass range 10^{-7}–10^{1} $M_{\odot}$ (Alcock et al. 1998; Lasserre et al. 2000; Tisserand & Milsztajn 2005). In fact, they appear to imply that the 10^{-3} $M_{\odot}$ objects suggested by Hawkins (1993, 1996, 2000, 2001, 2002) and the 10^{-5} $M_{\odot}$ objects suggested by Schild (1996) cannot contribute more than $\leq 10\%$ to the dark halo of the Milky Way. These local microlensing surveys do however have certain disadvantages. First of all, they do not directly constrain the cosmological density of compact objects, $\Omega_{\rm compact}$, but simply the MACHO mass fraction in a single dark halo. In principle, cosmic scatter in dark halo properties or compact objects mainly contributing to dark matter on super-galactic scales could complicate the conversion between these two quantities. More importantly, the local microlensing surveys are only sensitive to the densest microlenses. In order to produce strong microlensing effects, a compact object must be smaller than its own Einstein radius ($R_{\rm compact} < R_{\rm E}$). In Fig. 2.3, the maximum $R_{\rm compact}$ is plotted for microlenses detectable towards light sources at various distances. For light sources at cosmological distances $z \sim 1$, compact objects some ~ 100 times larger can be detected through microlensing effects than in the local Universe. Because of this effect, it is possible that a large dark matter population of rather diffuse objects could be missed by local microlensing surveys (e.g. Walker & Wardle 1999), and that such objects are in fact responsbile for the claimed detections towards high-redshift quasars.

What other constrains exist on compact objects in the subsolar mass range? Such objects are too massive to cause impacts on solar system bodies and too lightweight to interfere with stellar binaries (Carr & Sakellariadou 1999). Certain upper limits on such objects can be imposed by observations of multiply-imaged quasars (e.g. Schmidt & Wambsganss 1998; Wyithe et al. 2000a), but these are in general not very strong. Taken at face value, the strongest upper limits on $\Omega_{\rm compact}$ in the 10^{-4}–1 $M_{\odot}$ mass range instead appear to come from microlensing effects in quasars which are not multiply-imaged (Schneider 1993; Dalcanton et al. 1994). These methods are discussed in more detail in the following sections.

2.8 Summary of Paper I

In paper I, we revisit the method originally suggested by Canizares (1982) and first implemented by Schneider (1993) to impose upper limits on $\Omega_{\rm compact}$ in the 10^{-4}–1 $M_{\odot}$ mass range. This method is based on the idea that certain cosmologically distributed populations of compact objects (as depicted in Fig. 2.2) are expected to produce microlensing variations in quasars larger than the variations actually observed. Such populations can thereby be ruled

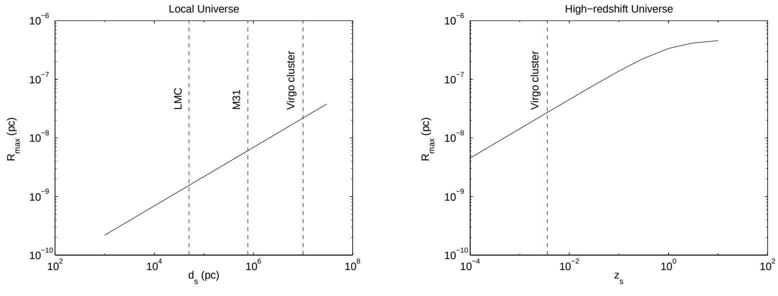

Figure 2.3: The maximum radius $R_{\rm max}$ that a compact object of mass 10^{-3} $M_\odot$ can have, while obeying $R \leq R_{\rm E}$, when observed towards a light source at distance $d_{\rm s}$ (left panel) or redshift $z_{\rm s}$ (right panel).

out. The fact that quasars are intrinsically variable at some level is in this case irrelevant, since adding two components of variability (e.g. intrinsic variations and microlensing) will in a statistical sense only increase the variations.

The original Schneider (1993) constraints were derived from the light curve amplitudes of 117 quasars monitored over a 10-year time span (Hawkins & Veron 1993). To predict how large the microlensing-induced variations from a given population of compact objects (characterized by their masses $M_{\rm compact}$ and their cosmological density $\Omega_{\rm compact}$) were expected to be, a numerical model was used. This model assumed an Einstein-de Sitter universe ($\Omega_{\rm M} = 1$, $\Omega_\Lambda = 0$) and used an approximation most suited for small light sources when calculating the contribution to the total magnification from each separate microlens. The limits on $\Omega_{\rm compact}$ presented furthermore assumed the velocity dispersion of the compact objects to be $\sigma_{v,compact} = 400$ km/s in directions perpendicular to the line of sight, and the typical size of the UV–optical continuum-emitting region in quasars to be $R_{\rm QSO} = 10^{13}$ m.

In Paper I, we work with the samples of Hawkins (2000), in total containing 386 quasars monitored over a time span of 20 years. For the analysis, we use a numerical model which is similar to that of Schneider (1993), but uses improved approximations in the case of large sources when estimating the magnification contribution from each microlens. The effects of magnification bias are also more carefully considered. The dependency of the results on the assumed values of $\sigma_{v,compact}$ and $R_{\rm QSO}$ are explored. All calculations are carried out in the framework of the currently favoured $\Omega_{\rm M} = 0.3$, $\Omega_\Lambda = 0.7$

cosmology.

In the standard model for quasars, the UV-optical continuum is assumed to arise in an accretion disk surrounding a supermassive black hole. If this is correct, the required mass of the SMBH in the centre of quasars sets a lower limit on $R_{\rm QSO}$. The gravitational radius of a SMBH is given by

$$R_{\rm g} = \frac{GM_{\rm SMBH}}{c^2} = 1.5 \times 10^{11} \frac{M_{\rm SMBH}}{10^8 \, M_\odot} \text{ m.} \tag{2.6}$$

For a static black hole, particles which happen to find themselves inside the so-called event horizon, or Schwarzschild radius, at $R_{\rm Sch} = 2 \times R_{\rm g}$, have passed the point of no return and cannot reveal themselves to the outside world. For a rotating Kerr black hole, the stable orbits may however continue all the way down to $R_{\rm g}$ (Rees 1984). Hence, the accretion disk which is believed to give rise to the UV–optical continuum, must at least be larger than $R_{\rm g}$, and accretion disk models typically predict $R_{\rm QSO} > 10$–$100\ R_{\rm g}$ (e.g. Koratkar & Blaes 1999; Collin et al. 2002). As discussed in Sect. 2.1, estimates of black hole masses in quasars indicate $M_{\rm SMBH} \geq 10^8\ M_\odot$, which means that the typical $R_{\rm QSO}$ should probably be *at least* a few times larger than $R_{\rm g} = 1.5 \times 10^{11}$ m.

In multiply-imaged quasars where microlensing is unambiguously detected, stronger constraints on the source size can be inferred. Since the amplitudes and durations of the microlensing events depend on both $M_{\rm compact}$ and source size (in fact also on source and lens velocities, although uncertainties in these are often neglected) the result is however a set of combined constraints on both of these quantities. Due to the demanding monitoring programmes and modelling efforts required to derive constraints of this type, estimates of the UV–optical $R_{\rm QSO}$ are currently limited to the two systems 2237+0305 and 0957+561 (e.g. Pelt et al. 1998; Refsdal et al. 2000; Wyithe et al. 2000b; Yonehara 2001; Shalyapin et al. 2002; Kochanek 2004). Typically, $R_{\rm QSO}$ is found to lie in the range 10^{12}–10^{14} m, which is the range explored in paper I as well. The dependence of $R_{\rm QSO}$ on redshift or luminosity is however largely unconstrained.

In paper I, we find that variations in $\sigma_{v,compact}$ (inside the 200–600 km/s range) do not have any dramatic impact on the $\Omega_{\rm compact}$ constraints derived. The value assumed for the typical $R_{\rm QSO}$ does however have a very pronounced effect on the outcome. In general, a larger source size implies smaller microlensing variations and less interesting constraints on dark matter. In the case of $R_{\rm QSO} = 10^{13}$ m, our strongest constraints imply $\Omega_{\rm compact} \leq 0.05$ for objects in the 10^{-3}–$10^{-1}\ M_\odot$ mass range, while at $R_{\rm QSO} = 10^{14}$ m, almost no useful constraints can be derived.

We furthermore demonstrate, that since microlensing effects are expected to be more important for high-redshift quasars, stronger constraints may be derived by using samples of high-redshift quasars only. This conclusion does however rely on the assumption that the typical $R_{\rm QSO}$ does not also become substantially larger with redshift. Whether this holds true or not depends on the redshift-dependence of the relation between quasar luminosity $L_{\rm QSO}$ and source size. Although the detailed $L_{\rm QSO}$–$R_{\rm QSO}$ relation tested (Czerny et al. 1994)[3] does indeed predict better constraints for high-redshift quasars, this is a highly model-dependent result. As the high-redshift quasars of a flux-limited sample are expected to have higher $L_{\rm QSO}$ than their low-redshift counterparts, and since one may expect high-$L_{\rm QSO}$ quasars to have larger accretion disks, $R_{\rm QSO}$ may very well grow with increasing $L_{\rm QSO}$, and hence with redshift. On the other hand, the light received in the optical from a high-redshift quasar was emitted at shorter wavelengths than from a low-redshift one. Since the accretion disk is typically expected to become bluer towards the centre, this may imply a *smaller* $R_{\rm QSO}$ for high-redshift sources. Hence, the exact $L_{\rm QSO}$–$R_{\rm QSO}$ relation depends on the quasar colour profile as a function of luminosity (and possibly also cosmic time).

In summary, this method of deriving constraints on $\Omega_{\rm compact}$ is promising, but unfortunately very sensitive to the poorly-known typical size of the region responsible for the UV–optical continuum.

2.9 Summary of Paper II

In Paper II, we address the issue of whether the observed long-term optical variability of quasars really can be attributed to microlensing, as suggested by Hawkins (1993, 1996, 2000, 2001, 2002). This is accomplished by comparing the statistics of observed quasar light curves to the statistics of microlensing light curves predicted by the model developed in Paper I. A time series analysis of this type can in principle be carried out in several different ways (see e.g. Vio et al. 1992). In this particular case, we do however not have direct access to the actual light curves, and are therefore largely limited to the previously published light curve statistics. Here, we restrict our analysis to the amplitudes (Hawkins 2000) and the average structure function (Hawkins 2001) derived from the light curves.

Our strategy is to simulate light curves for microlensing scenarios covering the entire plausible range of model parameters. By comparing these to their observed counterparts, the properties of the compact objects responsible for the observed variations can be constrained. In principle, this could be a promising way to derive the properties of the dark matter in the Universe, but as it turns out, this approach is fraught with difficulties.

[3] The numerical constant in (22) of paper I should read 1.07×10^{24} and not 3.37×10^{20}. This error only occurs in the printed article and not in the calculations performed. Carina Persson is acknowledged for bringing this misprint to my attention.

Although the analysis by Hawkins (1993, 1996) suggests that the mass of the microlenses must be $M_{\text{compact}} \sim 10^{-3}\ M_\odot$, we here explore a much more generous parameter space. We allow $\Omega_{\text{compact}} = 0.05$–$0.3$, $M_{\text{compact}} = 10^{-5}$–$1\ M_\odot$, $\sigma_{\text{compact}} = 200$–$600$ km/s and $R_{\text{QSO}} = 10^{12}$–10^{14} m. In total, some $\sim 15 \times 10^6$ simulated microlensing light curves are generated.

We find that microlensing reasonably well reproduces the average structure function of quasars, provided that most of the dark matter is in the form of planetary-mass compact objects ($\Omega_{\text{compact}} = 0.2$–$0.3$; $M_{\text{compact}} = 10^{-4}$–$10^{-3}\ M_\odot$), in agreement with the claims by Hawkins. The observed and simulated distributions of light curve amplitudes do however differ significantly. In particular, microlensing fails to explain the fraction of objects with amplitudes higher than 0.35 mag in the UV-excess based sample of Hawkins (2000). It also fails to explain the high amplitudes observed at low redshift ($z < 1$), where microlensing is less efficient as a variability mechanism due to the smaller distance to the quasars and hence a smaller number of compact objects along the line of sight. This means that microlensing *cannot* be the only mechanism relevant for the long-term optical variability of quasars. Our investigation is the first to demonstrate this.

While our results do not necessarily mean that a substantial population of planetary-mass MACHOs is ruled out, they do imply that the arguments used by Hawkins to claim the existence of such a population (and derive its characteristic properties) are invalid. This conclusion is consistent with the recent discovery of slight asymmetries in the observed long-term optical variability of quasars (de Vries et al. 2004).

2.10 Future prospects

As an alternative to the method used in Schneider (1993) and paper I for setting upper limits on Ω_{compact} in the subsolar mass range, another similar method – first implemented by Dalcanton et al. (1994) and later applied to a larger sample of quasars by Wiegert (2003) – can also be used. In this case, one takes advantage of the fact that the BLR of quasars is much larger than the region responsible for the optical continuum emission. Microlensing along the line of sight is therefore expected to increase the continuum flux, but leave the line emission relatively unchanged. If Ω_{compact} is high, this could cause a substantial fraction of quasars to display very low emission-line equivalent widths (weak line relative to continuum). This effect should furthermore become more pronounced with increasing quasar redshift. If this trend is not observed, upper limits on Ω_{compact} can be inferred.

In Zackrisson et al. (2004)[4], we demonstrate that while this method also

[4]largely based on results from the M.Sc. thesis by Persson (2003).

suffers from source size problems similar to those highlighted in paper I, the sensitivity to $R_{\rm QSO}$ is not as pronounced. For example, even for $R_{\rm QSO} = 10^{14}$ m, the $\sim 0.1\ M_{\odot}$ objects detected in the MACHO/EROS surveys must obey $\Omega_{\rm compact} \leq 0.1$ in an $\Omega_{\rm M} = 0.3$, $\Omega_{\Lambda} = 0.7$ universe. To the best of my knowledge, this is the strongest constraint available on the cosmological density (i.e. not just on the contribution to the dark halo of the Milky Way) of such objects. For $M_{\rm compact} < 0.1\ M_{\odot}$ objects, the uncertainties in the typical value of $R_{\rm QSO}$ nonetheless prevent firm conclusions on their possible contribution to the dark matter of the Universe.

Although the Space Interferometry Mission (SIM), scheduled for launch around 2010, will be able to resolve objects with unprecedented optical resolution, it is not expected to be able to directly resolve the actual accretion disk of quasars (Unwin et al. 2002). Installations of this type will however open up a new era in microlensing (Lewis & Ibata 1998; Treyer & Wambsganss 2004), as the additional quasar images caused by microlensing will become detectable. Such astrometric microlensing should be able to provide much stronger constraints on $R_{\rm QSO}$ from multiply-imaged quasars.

A large number of monitoring campaigns aimed at shedding new light on dark matter in the form of compact objects, both for light sources in the local Universe and at high redshift, are being planned or are already underway. The MEGA, POINT-AGAPE, WeCapp, Nainital and Angstrom collaborations have already started their search for MACHOs in the halo of M31, and SuperMacho is continuing the search for MACHOs towards LMC. The search for MACHOs through astrometric microlensing furthermore represents one of the SIM key projects.

With the monitoring of light sources at larger distances, the cosmological significance of more diffuse MACHOs can be assessed. The line of sight towards the giant elliptical galaxy M87 in Virgo cluster has been searched for microlensing events, with one tentative detection (Baltz et al. 2004), consistent with a populations of objects similar to that found in the MACHO survey. Monitoring of quasars located behind the Virgo cluster (Tadros et al. 1998, 2000) has produced certain upper limits on potential MACHO populations, although none very strong.

At even greater distances, Tuntsov et al. (2004) have suggested a search for microlensing effects towards gravitationally lensed arcs. A seemingly very efficient microlensing search can be conducted in the case where one happens to find two galaxy clusters located behind each other (Totani 2003), and a project of this type has been instigated to constrain the contribution from MACHOs in the 10^{-5}–$10^{10}\ M_{\odot}$ mass range to the cluster dark matter, down to a level of a few percent. As microlensing is expected to increase the scatter in absolute magnitudes of standard candles, the data coming in from planned supernova surveys like SNAP also seem very promising for constraining dark matter in the form of compact objects (Mörtsell et al. 2001; Minty et al. 2002).

If robust conclusions about the cosmological significance of MACHOs are to be made, the influx of new data will also require more sophisticated modelling, as current microlensing models are still very crude. As discussed in paper II, a particular concern for high-redshift light sources is the use of the Press & Gunn (1973) approximation when predicting the microlensing effects induced by MACHOs. A first step towards replacing this approximation with a more realistic prescription has recently been taken by the M.Sc. thesis by Riehm (2005).

3. The issue of non-cosmological redshifts

The notion that quasars are not located at the large distances implied by their redshifts, but rather situated nearby, dates all the way back (e.g. Hoyle & Burbidge 1966) to the discovery of the first quasars in the early 1960s (Schmidt 1963). To this date, a small number of astronomers still defend the view that a substantial part of the redshift measured in certain quasars may be non-cosmological in nature, i.e. not caused by the expansion of the Universe. If true, this could substantially undermine the use of these objects as probes of cosmology, since all current investigations of this kind (e.g. paper I & II) assume the observed redshift to be a tracer of distance. Circumstantial evidence in favour of such very controversial claims mainly come in the form of (for reviews, see Burbidge 1996, 2001):

- Apparent overdensities of high-redshift quasars in the field around low-redshift active galaxies, indicating a potential physical connection despite the large redshift discrepancy;
- Periodicities in quasar redshift distributions;
- High-redshift quasars curiously aligned along the minor axis of low-redshift active galaxies;
- Bridges of gas between low-redshift active galaxies and high-redshift quasars.

The least controversial of these is the apparent correlations in angular position between high-redshift quasars and low-redshift galaxies. These have been reported at high significance in several large catalogues (e.g Bartelmann & Schneider 1993, 1994; Norman & Impey 1999; Norman & Williams 2000; Gaztañaga 2003), and by prominent scientists not usually associated with claims of non-cosmological redshifts. In principle, such correlations could arise from gravitational lensing (amplification bias due to weak lensing and/or microlensing from the dark halo of the foreground galaxy), but so far, the attempts to model these effects have not been entirely successful (e.g. Benítez et al. 2001; Gaztañaga 2003).

The claims that the redshift distribution of quasars contains periodicities have a long history (see e.g. Cowan 1968; Karlsson 1971, 1977, for early reports of this type). According to the so-called Karlsson formula (Karlsson 1977) the quasars tend to pile up at redshifts separated by $\Delta\log_{10}(1+z) \approx$

0.089. This correlation appears to be particularly strong for quasars which have small angular distances to low-redshift galaxies (Karlsson 1990). The predicted sequence of redshift peaks at $z = 0.061$, 0.30, 0.60, 0.96, 1.41, 1.96 has subsequently been found to continue up to $z = 2.63$, 3.45 and 4.47 (Burbidge & Napier 2001). Within the framework of the standard models for quasar evolution and the expansion history of the Universe, there is no compelling reason why quasar activity should show any periodicity of this type. Peaks of this sort could however arise in the case of quantized, non-cosmological quasar redshifts superimposed on the Hubble flow (e.g. Bell & Comeau 2003, although these authors prefer a different function for the periodicity). The observed quasar redshifts z_{obs} would then be given by several components:

$$(1+z_{\text{obs}}) = (1+z_{\text{c}})(1+z_{\text{D}})(1+z_{\text{i}}), \tag{3.1}$$

where z_{c} is the cosmological redshift stemming from the expansion of the Universe (and hence an indicator of distance), z_{D} is the Doppler redshift due to peculiar motion and z_{i} represents the intrinsic quasar redshift, arising from some mechanism of unknown origin. Until recently, the quasar and galaxy samples used for studies of this type were however rather small and selected in heterogeneous ways, which could potentially give rise to spurious periodicity effects. With the latest surveys, like 2dF and SDSS, one would no longer expect this issue to be as severe. A recent search for periodicities in the 2dF redshift data for quasars projected close to foreground galaxies interestingly failed to detect any of the claimed periodicities (Hawkins et al. 2002). It was also argued that the previous detections of a periodic signal could be largely attributed to selection effects and flaws in the analysis. Other authors have however discovered redshift periodicities in both the 2dF and SDSS data sets (Bell 2004; Arp et al. 2005), and potential explanations for the failure of Hawkins et al. (2002) to detect these have been proposed (Napier & Burbidge 2003; Arp et al. 2005).

Arp and collaborators (e.g. Arp 1998; Chu et al. 1998) have discovered a large number of systems in which two or more quasars of similar redshifts appear to be distributed across the minor axis of a low-redshift active galaxies. Although configurations of this type could be produced through strong lensing effects, in which multiple images of a background quasar is produced by the foreground galaxy, the angular separation of the quasars in these associations is much larger ($> 1'$) than in known multiply-imaged systems where galaxies act as lenses ($< 5''$, see e.g. Claeskens & Surdej 2002). The mainstream explanation for these systems is instead that the apparent alignments arise because of selection effects. Obviously, quasars will appear to cluster around the minor axis if this is the only field around the foreground object which is being searched. The detections of bridges of gas between galaxies and quasars of different redshift (e.g. Sulentic & Arp 1987) are often suspected to be due to chance projection.

Despite all these claims of non-cosmological redshifts, there is of course strong evidence that many quasars are in fact located at the distances implied by their redshifts. The discovery of galaxies and quasars located close in the sky and having very similar redshifts (Stockton 1978), suggesting membership to the same group or cluster, strongly suggests that the observed redshifts are indeed cosmological in nature. If quasars are to explain a substantial part of the observed X-ray background, as is generally assumed, a lower limit on the average quasar distance may also be inferred, indicating that only a small fraction of quasars can be truly local, i.e. located within a distance of 200 Mpc (Burbidge 1996).

Although I have here only reviewed the claims of non-cosmological redshifts in quasars, it should however be noted that a rich literature on reported redshift anomalies in galaxies and galaxy clusters also exists (see e.g. Tifft 1996; Arp & Russell 2001; Bell & Comeau 2003).

If the redshifts of certain quasars are indeed largely non-cosmological, what would be the implications? Although very far-reaching modifications of the standard cosmology have been suggested to explain these redshift anomalies (e.g. Narlikar & Arp 1993; Narlikar & Padmanabhan 2001), the necessity for such radical actions is not at all clear. The impact of non-cosmological redshifts on extragalactic astronomy and cosmology must necessarily depend on the underlying mechanism for these anomalies, as well as the fraction of the quasar population that is affected.

Clearly, it would be highly desirable to somehow bring closure to the infected issue of non-cosmological redshifts. One of the reasons why this is not easily accomplished is that the claims of this type are so disparate (and sometimes vague) that they cannot easily be falsified (see e.g. Burbidge 1996, for a discussion). In the following section, I do however discuss a number of potential tests which could severely constrain claims of this type.

3.1 Potential tests of non-cosmological redshifts in quasars

An evolutionary scenario which incorporates many of the claimed quasar redshift anomalies has been advanced by Arp and collaborators (see e.g. Arp 1998). The basic, very controversial idea is that high-redshift quasars can be ejected from the centre of the low-redshift, active galaxies, and that correlations in angular position between these objects is evidence of this. It is furthermore argued that the ejected quasars, through some still unknown mechanism, evolve into normal galaxies (or even clusters of galaxies – see Arp & Russell

2001) with the same redshift as that of their "mother galaxies".

Although the mere existence of quasar absorption systems (at redshifts intermediate between that of the quasar and its claimed parent) or quasar host galaxies is often taken as evidence that such claims must be nonsense, neither directly contradicts the ejection scenario. In principle, the former may be interpreted as gas which itself has a component of non-cosmological redshift and is associated with the halo of the mother galaxy, and the latter as a transition object in the state of evolving from a quasar into a galaxy (Burbidge 1996).

If quasars truly are ejected at substantial velocities, their positions in the sky should of course slowly shift if monitored for a sufficiently long period of time. The expected change is however so small, that very high precision is required to measure their proper motions. As recently demonstrated by Popowski & Weinzierl (2004), this should however be possible with proposed satellites like GAIA or SIM, or even at the present time with an 8 m class telescope.

In the following, I propose a number of complementing tests, some of which require much more modest observational facilities.

3.1.1 Quasar absorption systems

Although the existence of quasar absorption systems does not necessarily falsify the ejection scenario, their detailed properties very well could. Small, low-density gas clouds along the line of sight are known to produce large numbers of narrow Lyman-α absorption lines (the so-called Lyman-α forest) on the short-wavelength side of the Lyman-α emission line in the spectrum of quasars. The redshift distribution of these lines is furthermore statistically consistent with the known properties of the large-scale structure of the universe (e.g. Weinberg et al. 2003). If this interpretation is correct, and if most quasars are accepted to lie at the distances implied by their redshifts, it would be rewarding to investigate the redshift distribution of the Lyα forest lines for the quasars located in the quasar-galaxy associations claimed to represent the best cases in favour of non-cosmological redshifts. If these associations are real, a distribution of absorber redshifts inconsistent with that of quasars in the normal population should be found, as the distributions arise from completely different mechanisms (large scale structure versus ejection with intrinsic redshifts).

An alternative way could be to search for galaxies close to the line of sight towards quasars (at redshift z_{QSO}) claimed to have been ejected from low-redshift objects (at z_{parent}). If the redshift of such a galaxy would match that of an absorption feature with redshift z_{abs} in the quasar spectrum, and obey $z_{\mathrm{parent}} < z_{\mathrm{abs}} < z_{\mathrm{QSO}}$, it would according to the standard interpretation of redshift be located inbetween the quasar and the so-called parent galaxy. By establishing, by some independent method, that the distance to this absorbing galaxy is in fact much higher than that of the parent, the association would be proved to be a projection effect. Since the absorber must be gas-rich, the most appropriate distance indicator in this case is probably the Tully-Fisher relation (Tully & Fisher 1977, see also Sect. 4.2) for disk galaxies, as this can currently be used up to a redshift of $z \approx 1.5$ (e.g. Barden et al. 2003). The main problem with this approach is its low efficiency. Even in the case of very strong absorption features, like damped Lyman-α clouds, attempts to identify the culprit galaxy often fail. Even if one is found, it would have to be a disk galaxy at a suitable inclination (not too close to face-on) in order for the Tully-Fisher relation to be applicable. This means that only in a small fraction of the high-redshift quasars probed, can physical associations to low-redshift galaxies realistically be ruled out. The probability for a spurious match between the redshift of a quasar absorption feature and some galaxy close to the line of sight must also be carefully assessed.

3.1.2 Quasar host galaxies

Building on the ejection scenario outlined in Arp (1998), Bell (2002) has constructed a more detailed model, calibrated on quasars found in the vicinity of the active galaxy NGC 1068. In this scenario, quasars are ejected from the centre of active galaxies at near-relativistic velocities (≤ 0.1 c) and initially large components of non-cosmological redshifts. As the quasar travels outwards, the intrinsic redshift drops while the luminosity increases. After some period ($\leq 10^8$ yr long), the intrinsic redshift component will be negligible and the object will no longer manifest itself as a quasar. According to the scenario proposed by Arp (1998), the object will at this point have evolved into a low-luminosity galaxy. As argued in paper III (see Sect. 3.2), this model requires that the host galaxies of the quasars which are claimed to have been ejected must possess some very unusual properties, which can be tested with a modest investment of telescope time.

3.1.3 Quasar luminosities

Even though quasars are not good standard candles (for instance because they display stochastic variability), the optical luminosity function (e.g. Boyle et al. 2000) derived from the standard assumption that the observed redshift is a good tracer of distance does however imply that most quasars at a given redshift (in a survey with typical flux limits) will fall within ~ 3 magnitudes of each other in absolute magnitude. One may expect that incorrectly postulating that some of the high-redshift quasars are in fact located nearby would increase this scatter. Although the catalogue of claimed quasar-galaxy associations presented in Burbidge (1996) has a very complicated selection function, it could be used as a starting point to search for this effect. If the increased luminosity dispersion is confirmed, this would imply that either the claimed associations are just spurious, or that only a minority of quasars can be subject to substantial non-cosmological redshifts. A similar test can also be applied for the claimed non-cosmological redshifts in galaxy clusters, as the brightest galaxies of rich galaxy clusters display a very narrow range of absolute magnitudes when assumed to lie at the distances implied by their redshifts. If a Gaussian is fitted to the absolute magnitudes of the brightest cluster galaxies, the dispersion is only 0.28 magnitudes (Bernstein & Bhavsar 2001). Tampering with the distances is therefore likely to increase the scatter substantially.

3.1.4 Quasar colours

If the notion of two separate populations of quasars – some which have been ejected and some which have not – is taken seriously, it would be very curious if these two classes of objects were to appear identical in all observables other than redshift, despite (probably) having very different fueling mechanisms. It would therefore be interesting to statistically compare the colours or spectral properties of quasars located in the quasar-galaxy associations claimed to constitute the best cases in favour of ejection to a general sample of quasars. If the former turn out to be located inside a very limited region of the colour space spanned by the latter, this would indicate that the former truly do belong to a separate population. A large, homogeneous multi-colour survey, like the SDSS, would be ideal for this investigation.

3.2 Summary of Paper III

In this paper, one of the methods outlined in the previous section is explored in more detail. According to the ejection scenario advanced by Bell (2002), quasars are ejected from the centre of active galaxies (as previously suggested by e.g. Arp 1998) at near-relativistic velocities (≤ 0.1 c) and initially large components of non-cosmological redshifts. As the object travels outwards, the intrinsic redshift drops and the luminosity increases. After $\leq 10^8$ yr, the intrinsic redshift component will have become negligible and the object will no longer manifest itself as a quasar.

As argued in paper III, this model appears to be at odds with current data on quasar host galaxies. In the standard picture, quasars are fueled by SMBHs located in the centre of galaxies. Even though the quasar AGN is often bright enough to completely outshine its host galaxy, various techniques can be employed to obtain information about the host. They all take advantage of the fact, that while the quasar nucleus is close to a point-source, the surrounding galaxy is more extended. Although a spectrum taken across the centre will be completely dominated by the AGN, a spectrum taken at some off-nucleus position will reveal the underlying host. A number of image processing techniques (see e.g. Örndahl 2003, and references therein) have also been developed to subtract the point source from the image of the quasar, leaving the host galaxy as the residual.

By examining the quasars in the quasar-galaxy associations claimed to provide with the best evidence for non-cosmological redshifts, one would expect to find – provided that the quasars involved really have been ejected in the way proposed by Bell (2002) – either:

1. No host at all (because the transition from quasar to galaxy has yet to start, or because the host may be unusually faint or small);
2. A host consisting only of gas ionized by the quasar. This gas may either have been ejected along with the quasar (as indicated by the claimed bridges) or have been produced by the ejected object itself. Such gas production would at some point be required if the ejected quasars are in fact to evolve into normal galaxies;
3. A host consisting only of gas and young stars with ages lower than 10^8 years.

These predictions stand in sharp contrast to the current understanding of quasar host galaxies. Despite early claims of detections of quasars with no host galaxy (Bahcall et al. 1994, 1995), a general consensus has emerged that most quasars, if not all, are in fact hosted by galaxies. In cases where host galaxies are not found, the non-detections can typically be attributed to the faintness of the host relative to the active nucleus at the sampled wavelengths or problems in subtracting the nuclear component due to the small angular size of the host, as in the case for quasars at high redshift. By targeting low-redshift quasars and going sufficiently deep in suitable passbands, one does however expect to detect the hosts unless they are unusually faint or small compared to the hosts discovered so far. If the hosts of quasars located in peculiar quasar-galaxy associations systematically should turn out to have either of these characteristics, this would indicate that they indeed stem from a separate population.

The majority of quasar host galaxies studied at low redshifts so far (e.g Nolan et al. 2001; Jahnke et al. 2004) appear to have spectral energy distributions characteristic of stellar populations at least a couple of Gyr old. As demonstrated in paper III, both the options (2) and (3) above would produce host galaxy spectra much bluer than this in the optical to near-IR wavelength range. Hence, many quasars appear not to have been ejected in the way suggested by Bell (2002). Although broadband colours are generally poor probes of the ages of galaxies (see e.g. paper IV), the situation predicted by the Bell (2002) model is so extreme that they should be quite adequate for a first implementation of the proposed test.

4. Low surface brightness galaxies as probes of dark matter

4.1 Low surface brightness galaxies

Low surface brightness galaxies (LSBGs) are galaxies in which the surface flux density (typically given in units of either $L_{\odot}$ pc^{-2} or mag arcsec^{-2}) is much lower than what was once assumed to be representative for disk galaxies (the Freeman value, $\mu_{\mathrm{B},0} = 21.65$ mag arcsec^{-2}, for the *B*-band central surface brightness $\mu_{\mathrm{B},0}$; Freeman 1970). This property makes them enigmatic in many respects.

Already Zwicky (1957) realised that galaxies at surface brightness levels comparable to or fainter than that of the night sky ($\mu_{\mathrm{B}} \approx 23$ mag arcsec^{-2} at the darkest sites on Earth) would be very difficult to detect, and that this could give rise to a significant bias in galaxy catalogues. It has since been firmly established that a huge population of LSBGs, due to their low contrast compared to the sky background, did in fact evade detection in early galaxy surveys. In fact, the claimed universality of the Freeman value turned out to stem from selection effects of this type. Even today, the cosmological significance of LSBGs is not completely clear. The number density of galaxies appears to stay constant down to the faintest central surface brightness levels probed ($\mu_{\mathrm{B},0} \approx 25$ mag arcsec^{-2}; e.g. O'Neil & Bothun 2000), meaning that LSBGs greatly outnumber the high surface brightness Freeman galaxies. Whether there may still lurk even more ghostlike galaxies below the detection threshold of current surveys is still something of an open question (e.g. Minchin et al. 2004).

Why do some galaxies become LSBGs while others do not? For some reason, star formation in these objects appears to have been relatively inefficient, leading to low luminosity densities, low metallicities and high gas fractions. A scenario which has attracted much attention during recent years is the notion that LSBGs form inside dark halos with unusually high angular momentum. Although the particle trajectories inside dark halos are largely random, a small primordial component of net rotation is expected to develop as the halos gain angular momentum from tidal interaction with neighbouring structures at an epoch when the halo was just a modest overdensity of matter, and had not yet decoupled from the expansion of the Universe (Barnes & Efstathiou 1987).

During the subsequent merger history of the halos, their mean angular momentum is expected to increase. Current simulations can predict the statistical distribution of angular momentum among CDM halos, and indicate that their present angular momentum typically lies at a few percent of that required for rotational support.

As the baryons inside these dark halos dissipate and collapse, it is commonly assumed that the angular momentum is preserved. Since the angular momentum creates centrifugal support against collapse, a disk should form with a scale length related to the amount of angular momentum (or spin) of the original halo. Whereas high-spin halos are expected to produce extended, low-density disks, low-spin halos would create smaller and more concentrated disks. Theoretical arguments concerning the dynamical stability of disks indicate that low surface density disks should be more stable against star formation (Toomre 1964), and observationally, star formation in disks does indeed appear to become strongly suppressed once the gas surface density drops below a limit of ~ 5–$10\ M_{\odot}\ \mathrm{pc}^{-2}$ (Kennicutt 1998), where LSBGs are found (van der Hulst et al. 1993). From this point of view, the notion that LSBGs are associated with high spin halos does appear reasonable.

4.2 The dark matter properties of low surface brightness galaxies

LSBGs are particularly interesting for dark matter research, since the mass-to-light ratio (M/L) has been observationally found to increase with decreasing surface brightness (McGaugh & de Blok 1998), meaning that LSBGs are more dark matter dominated than their high surface brightness counterparts.

Since most LSBGs are disk galaxies, the M/L-ratio can be derived by combining the observed luminosity with the mass derived from the rotation curve. Under the assumption of circular orbits in a spherical mass distribution, the mass $M(R)$ contained inside the radius R from the centre of the disk by:

$$M(R) = \frac{RV(R)^2}{G}, \tag{4.1}$$

where $V(R)$ represents the circular velocity at R. As discussed by Zwaan et al. (1995) and McGaugh & de Blok (1998), the high M/L of LSBGs also follows from the fact that LSBGs obey the Tully-Fisher relation (Tully & Fisher 1977), an empirical relation between the width of the 21 cm HI emission line, which reflects the asymptotic rotational velocity V_{c}, and the luminosity L. The Tully-Fisher relation can be written:

$$V_{\mathrm{c}}^{x} \propto L_{\mathrm{f}}, \tag{4.2}$$

where f represents the photometric filter in which the luminosity has been measured and x is the f-dependent slope of the relation. Most studies so far have found $x \approx 4$ (e.g. Tully & Verheijen 1997). By defining a surface mass density $\sigma(R)$ as

$$\sigma(R) = \frac{M(R)}{\pi R^2}, \tag{4.3}$$

it follows from (4.1) that

$$V(R)^4 = \pi G^2 M(R)\sigma(R). \tag{4.4}$$

Now, by definition

$$M(R) = \frac{M(R)}{L_{\rm f}(R)} L_{\rm f}(R), \tag{4.5}$$

and

$$\sigma(R) = \frac{M(R)}{L_{\rm f}(R)} \frac{L_{\rm f}(R)}{\pi R^2}, \tag{4.6}$$

where $L_{\rm f}(R)$ is the luminosity inside R. Substitution of (4.5) and (4.6) into (4.4) implies that

$$V(R)^4 \propto (\frac{M(R)}{L_{\rm f}(R)})^2 (\frac{L_{\rm f}(R)}{\pi R^2}) L_{\rm f}(R). \tag{4.7}$$

By comparing this to (4.2), one realises that the term $(\frac{M(R)}{L_{\rm f}(R)})^2(\frac{L_{\rm f}(R)}{\pi R^2})$, i.e. the mass-to-light ratio squared, times the surface brightness, has to be kept constant in order to recover the Tully-Fisher relation. Hence, low surface brightness must imply a high mass-to-light ratio.

In a sufficiently dark matter dominated system, the visible baryons would have negligible impact on the gravitational potential of the system and would serve as mere test particles of the dark halo mass distribution. Since the dynamical properties of baryons are a good deal more complicated than those assumed for dark matter (as e.g. in the CDM model), getting rid of the baryonic influence is highly desirable when attempting to recover the dark halo density profile. As the total M/L of galaxies has been shown to increase with both decreasing surface brightness and luminosity (e.g. McGaugh & de Blok 1998; Mateo 1998), LSBGs and dwarf galaxies have become popular targets for testing the predictions of various dark matter models. As discussed in Sect 1.6.1, most such investigations have so far failed to verify the predictions of the CDM scenario.

4.3 Summary of Paper IV

In paper IV, a sample of extremely blue LSBGs is investigated for the purpose of shedding light on the properties of their stellar populations. Using a combination of optical and near-IR broadband photometry, together with Hα emission line data, we attempt to constrain the star formation histories, ages, total stellar masses and stellar mass-to-light ratios of these objects. To accomplish this, spectral evolutionary models are used. These are numerical models which, given a number of input parameters, predict the electromagnetic spectrum for a stellar population (i.e. a star cluster or a galaxy). The relevant parameters which regulate the properties of a stellar population are often taken to be:

- The age of the population.
- The star formation history (SFH), i.e. the prior evolution of the rate by which gas is tranformed into stars (in $M_{\odot}/\mathrm{yr}$).
- The stellar initial mass function (IMF), i.e. a function which describes how common it is for a star to be born with a certain mass. Often, this is assumed to follow a power-law of the type $dN/dM \propto M^{-\alpha}$ inside some interval $[M_{\mathrm{low}}, M_{\mathrm{up}}]$.
- The temporal evolution of the metallicity $Z(t)$ of the stellar population, where Z represents the mass fraction of elements with atomic number higher than that of helium.

Many systems also require additional parameters which regulate the properties of their interstellar medium (gas and dust content). Of course, neither the stellar nor interstellar parameters are in most cases known a priori. One may then instead work backwards, and use observed properties (e.g. spectra, line-ratios, colours) to constrain the model parameters, and thereby – provided that the model is sufficiently realistic – the physical properties of the target objects.

In paper IV, two spectral evolutionary models are used: the Zackrisson et al. (2001) model and PÉGASE.2 (Fioc & Rocca-Volmerange 1999). Although a large number of similar models exist (e.g. Leitherer et al. 1999; Bruzual & Charlot 2003; Bicker et al. 2004), these two are at the current time among the few which:

1. Allow predictions to be made for a wide range of SFHs, ages and IMFs;
2. Allow the use of arbitrary broadband filters when converting the predicted spectra into photometric data;
3. Include the effects of both nebular emission lines and continuum.

For each model, a grid of model parameter values is used to generate a large set of synthetic spectra. From these, broadband magnitudes and emission-line data are derived and compared to the observations. Fig. 4.1 illustrates the spectral evolution of a stellar population predicted by the Zackrisson et al. (2001)

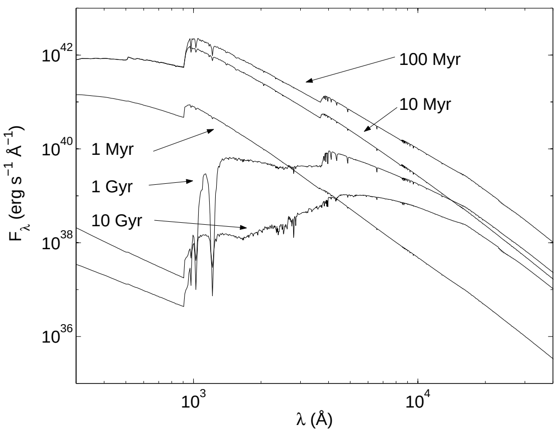

Figure 4.1: The spectral evolution predicted by the Zackrisson et al. (2001) model for a low-metallicity ($Z = 0.001$) stellar population (without nebular emission) which forms stars at a constant rate of 100 $M_\odot$ yr^{-1} during the first 100 Myr, but none thereafter. The ages at which the plotted spectra are representative have been indicated.

model.

When using the observed kinematics of a galaxy to investigate the properties of its dark halo (as in Paper V), it becomes important to establish the mass contribution of the stellar population, so that it may be corrected for. Here, we derive the range of stellar population M/L-ratios allowed (in filters $BVRiIJHK$, under standard assumptions about the IMF) by successful fits of models to the available observations for these extremely blue LSBGs.

As discussed in Sect. 4.1, many contemporary models for the formation and evolution of LSBGs assume these objects to form inside dark matter halos of unusually high spin. A detailed model of this kind has been presented by Boissier et al. (2003). Due to the assumed relation between gas infall and mass density of the disk (see Boissier & Prantzos 2000), this model predicts that galaxies at low masses and/or low surface brightness levels should have

SFHs in which the star formation rate is constant or increases from a few Gyr after Big Bang and up until the present time. In paper IV, we demonstrate that the observed Hα equivalent widths (which measure how strong this emission-line is compared to the underlying continuum) are inconsistent with this prediction, unless a non-standard IMF deficient in high-mass stars is assumed. Interestingly, a similar IMF has recently been suggested (Lee et al. 2004) to explain the number of spiral arms seen in LSBGs (Fuchs 2003), and could imply that the disks of LSBGs are more massive than usually assumed.

According to the CDM paradigm (as opposed to the case for HDM), dark matter halos should form hierarchically in a bottom-up sequence. In this scenario, low mass-objects form first whereas higher-mass objects are predicted to form through mergers at later epochs. Naively, one would expect the stars in the galaxies located inside these halos to follow a similar scheme, and this is in fact what is predicted by most current models (e.g. Nagamine et al. 2001). This simple picture has nonetheless been questioned by observations which indicate anti-hierarchical relations between mass and mean stellar ages in low-redshift galaxies (e.g. Jimenez et al. 2005), and by the discovery of massive galaxies apparently assembled already at high-redshift (see e.g. Thomas et al. 2002, for a review). Here, we find that the total mass in stars and neutral hydrogen gas in our target galaxies is sufficiently small to allow a similar kind of test. According to the hierarchical picture, galaxies of this mass should form early in the history of the universe. Yet, the blue colours of our objects (indicating the presence of young stars) could be interpreted as due to a fairly recent formation epoch. Although a few stragglers are expected even in the hierarchical picture, we demonstrate that galaxies of the type investigated here are sufficiently numerous in the local universe to provide an interesting test. We find, however, that due to a degeneracy between age and star formation history in broadband photometry, we are unable to determine the exact age of these objects from available optical/near-IR data. Although they could have formed as recently as 1–2 Gyr ago, ages as high as the current age of the Universe ($14.1^{+1.0}_{-0.9}$ Gyr; Tegmark et al. 2004) cannot be ruled out, if the star formation history is allowed to be sufficiently extended. In discussing a number of observations which could improve the age constraints, we find that UV data may be one of the most promising ways. This conclusion is supported by an analysis of similar parameter degeneracies by Gil de Paz & Madore (2002).

4.4 Summary of Paper V

In this paper, we investigate the kinematics of a sample of extremely blue LSBGs (similar to those analyzed in paper IV) in order to gain insight about the properties of their dark halos.

Although the CDM model has been very successful in explaining the formation of large scale structure in the Universe, it has run into a number of problems on the scales of galaxies (see Sect. 1.6.). In particular, many simulations of structure formation based on the CDM scenario predict the dark matter density to rise dramatically (a density cusp) in the centre of dark halos (e.g. NFW, Navarro et al. 2004; Reed et al. 2005; Fukushige & Makino 2003), while most attempts to measure the slope of the innermost density profile instead have revealed what appears to be a constant density core (e.g. de Blok & Bosma 2002; Blais-Ouellette et al. 2001; Gentile et al. 2004).

A few detections of bona-fide density cusps nonetheless exist (see individual objects in de Blok & Bosma 2002; Swaters et al. 2003; Simon et al. 2004), which raises the question of whether the constant density cores are artefacts of systematic observational problems (as suggested by e.g. Swaters et al. 2003; Spekkens & Giovanelli 2005), or whether we are witnessing true cosmic scatter in halo properties. Another alternative is that some poorly understood process – not yet considered in the N-body CDM simulations – may remove the central density cusp in certain objects. In the context of trying to distinguish between these possibilities, it becomes important to establish which observable galaxy properties correspond to which halo properties.

For several reasons, the very centre ($R < 1$ kpc) of galaxies is quite possibly not the best site to test the viability of the CDM scenario. The theoretical predictions for the CDM halo profile are still very shaky at small radii due to insufficient resolution in current N-body simulations (e.g. Power et al. 2003). The observations made in this region may in principle also be affected by a host of systematic problems (e.g. Swaters et al. 2003; Rhee et al. 2004). In the very centre, there is furthermore the possibility that baryons dominate the mass budget, thereby introducing a bias on the inferred halo properties which is difficult to control at present. Substantial deviations from the CDM predictions do however also occur at larger radii. Both the average shape of the rotation curve of LSBGs (e.g. McGaugh & de Blok 1998) and the average density inside a radius of a a few kpc (e.g. Alam et al. 2002) is in substantial disagreement with current CDM predictions.

Here, we study a class of LSBGs not previously targeted for studies of this kind. The objects have been selected on the basis of very faint low surface brightness levels in the centre and very blue colours. As argued in paper V, these properties may possibly minimize the contribution from baryons to the mass budget in the centre. Long-slit spectroscopy is carried out both along the major and minor axis of the disks in these objects, using the FORS2 instrument at the VLT/UT4 Yepun 8.2 m telescope in Chile. To correlate kinematics with optical properties, broadband photometry in BVI is also performed. From these data, the properties of the density profile both in the centre and at greater radii are derived and compared to the predictions of the CDM model.

Although several of our target objects display very disturbed kinematics which complicates the analysis, the halo properties that we derive are not in accord with the standard CDM model. None of the objects for which we are able to derive the central density profile show any signs of a CDM density cusp as steep as that originally predicted by NFW. Furthermore, the average density $\Delta_{V/2}$, inside the radius at which the rotational velocity has dropped to half its maximum value, is more than one order of magnitude lower than predicted in the ΛCDM scenario. The constraints imposed on $\Delta_{V/2}$ by these extremely blue LSBGs are among the strongest available.

A recently suggested resolution to the core-cusp problem is that the CDM cusp may be removed by feedback associated with a fast collapse phase (Mo & Mao 2004), which is also responsible for the creation of the bulges of galaxies. In this scenario, bulgeless galaxies should still display the original density cusp. As our target objects neither show any sign of bulges nor CDM density cusps, the observations presented in paper V do not favour this scenario. The minor axis kinematics of our targets furthermore show no sign of the signature predicted by Hayashi et al. (2004) for an elliptical disk inside a triaxial dark halo potential, which has been proposed as another way of reconciling the CDM model with observations.

Many of the bluest LSBGs are known to be underluminous in the centre compared to the exponential profile usually seen in disk galaxies (Bergvall et al. 1999). In this paper, we demonstrate that the break in the central light profile does not display any obvious correlation with features in the rotation curves or derived density profiles. The origin of this central light deficiency remains a mystery.

4.5 Future prospects

Although the observational constraints on dark matter halos have substantially improved with the wide-spread use of optical, long-slit rotation curve data as a complement to low-resolution HI rotation curves, this technique is still fraught with uncertainties (e.g. Swaters et al. 2003). Many of the problems associated with non-circular motions can be better addressed by two-dimensional velocity fields obtained through multiple-fibre spectrographs or Fabry-Perot interferometers, and several investigations of this kind have already been instigated (e.g. Blais-Ouellette et al. 2001; Simon et al. 2004). So far, no universal halo profile does however seem to emerge, indicating that the scatter is cosmic rather than due to observational problems.

One of the big future challenges in the game of putting the CDM predictions to the test will be to connect the observed properties of galaxies to those of their dark halos. Do the observationally established halo properties correlate with colour, central surface brightness (disk or actual), baryonic mass, disk scale length, disk thickness or other properties? Until these very complicated issues are resolved, the bias introduced by testing the average CDM halo properties against the dark halos of some particular class of objects – such as dwarf galaxies or LSBGs – will be hard to control. Stronger constraints on the influence of dark baryons on the observed kinematics of galaxies are also badly needed.

On the theoretical side, the resolution of N-body CDM simulations needs to be increased to the level of current observations, so that the severity of the central core/cusp discrepancy in galactic halos becomes clear. The simulations furthermore need to evolve from the stage of providing predictions for the spherically averaged, dark halo density profiles to giving predictions for the kinematics of baryons inside the actual (triaxial) potentials of these dark halos. Although certain steps in this direction have already been taken (e.g. Hayashi et al. 2004), there is still a long way to go.

5. Appendix: Symbols and abbreviations

Table 5.1: *Table of commonly used abbreviations*

Abbreviation	Explanation
AGN	Active Galactic Nucleus / Nuclei
BBNS	Big Bang Nucleosynthesis
BLR	Broad-Line Region
CDM	Cold Dark Matter
CMBR	Cosmic Microwave Background Radiation
HDM	Hot Dark Matter
IMF	Initial Mass Function
IR	Infrared
LMC	Large Magellanic Cloud
LSBG	Low Surface Brightness Galaxy
MACHO	Massive Astrophysical Compact Halo Object
MOND	MOdified Newtonian Dynamics
NFW	Navarro, Frenk & White (Navarro et al. 1996, 1997)
SDSS	Sloan Digital Sky Survey
SFH	Star Formation History
SMBH	Supermassive Black Hole
SMC	Small Magellanic Cloud
UV	Ultraviolet
WIMP	Weakly Interacting Massive Particle

Table 5.2: *Table of frequently used symbols*

Symbol	Explanation
$'$	Arcminute
$''$	Arcsecond
a	Cosmic scale factor
c	Speed of light or NFW concentration parameter
D	Distance
$\Delta_{\mathrm{V/2}}$	Central density parameter
G	Gravitational constant
H_0	Current value of the Hubble parameter
HI	Neutral hydrogen
H_2	Molecular hydrogen
HeI	Neutral helium
λ	Wavelength
k	Cosmic curvature parameter
L	Luminosity
L_{E}	Eddington luminosity
$L_{\odot}$	Solar luminosity
M	Mass
$M_{\odot}$	Solar mass
μ	Surface brightness or MOND interpolation function
n	Number density
Ω	Cosmic density parameter
ρ	Density
p	Pressure
R	Radius
v or V	Velocity
z	Redshift
Z	Metallicity

6. My contribution to the included papers

- **Paper I.** Most of the microlensing code used in this paper and in paper II was written by me, although some parts come from the work of Gullerström (2000). I carried out the analysis and wrote most of the paper. Nils Bergvall estimated the likely range of lens and quasar velocities and wrote the paragraphs related to that.
- **Paper II.** I carried out the analysis and also wrote the paper. Thomas Marquart developed the software used to calculate the average structure function from samples of simulated light curves, as part of his M.Sc. thesis (Marquart 2002) supervised by me. Phillip Helbig gave useful advice on the calculation of angular size distances with the publicly available code that he helped develop (Kayser et al. 1997).
- **Paper III.** I invented the proposed test, carried out the calculations and wrote the paper. The code used to convert the spectra from the Zackrisson et al. (2001) model into broadband fluxes at various redshifts was however kindly provided by Nils Bergvall.
- **Paper IV.** I carried out the analysis and wrote most of the paper. Nils Bergvall provided the observational data, estimated the contribution of blue LSBGs to the total population of galaxies in the local Universe and wrote part of the paper. Göran Östlin looked into the possibility of using absorption line data to improve the age constraints and provided useful comments on the manuscript.
- **Paper V.** I reduced the spectroscopic data, carried out the analysis and wrote the paper. Nils Bergvall reduced the photometric data and computed the surface brightness profiles. Thomas Marquart helped in preparing the service observations, while Göran Östlin gave useful comments on the application for observing time and on the manuscript.

7. Summary in Swedish

Kvasarer och ytljussvaga galaxer som redskap för att studera den mörka materian

Mörk materia

Under de senaste 70 åren har stora observationella och teoretiska landvinningar inom astronomin lett fram till den häpnadsväckande slutsatsen att materian som vi kan se i våra nuvarande teleskop bara utgör ett par procent av den totala materiamängden. Den återstående delen utgörs av så kallad mörk materia, som varken utsänder eller absorberar ljus. Vad denna viktiga komponent egentligen består av är fortfarande ett mysterium. I denna avhandling undersöks möjligheterna att utnyttja två välkända astronomiska objekt, kvasarer och ytljussvaga galaxer, för att närmare undersöka den mörka materians natur.

Kvasarer

Kvasarer är extremt ljusstarka objekt, vars strålningsenergi alstras när materia dras ned i ett s.k. supermassivt svart hål i centrum av en avlägsen galax. I artikel I och II undersöks möjligheten att den mörka materian kan utgöras av mörka, kompakt föremål med en massa någonstans mellan solens och jordens. Ett antal observationer antyder redan att både vår och andra galaxer innehåller stora mängder av sådana objekt. Vad dessa objekt egentligen är och hur mycket de eventuellt skulle kunna bidra till universums mörka materia är däremot oklart.

Enligt Einsteins allmänna relativitetsteori kan ljusstrålar från avlägsna ljuskällor krökas av massansamlingar längs synlinjen. Sådana gravitationslinseffekter gör det möjligt att detektera mörk materia trots att den inte utsänder något ljus. I artikel I och II används numeriska modeller för att undersöka hur s.k. mikrolinseffekter, som uppkommer när kompakta, mörka objekt råkar passera synlinjen, påverkar ljuset som vi mottar från kvasarer.

Om bidraget till universums materiainnehåll från kompakta objekt är tillräckligt högt, förutspår de numeriska modellerna att kvasarernas ljusvariationer borde vara större än vad som faktiskt observeras. En sådan hög andel kompakta objekt kan då uteslutas. I artikel I används denna metod för att sätta övre gränser på andelen mörk materia i kompakta objekt av olika massor. Vi visar att det allvarligaste problemet med denna teknik är den stora osäkerhet som finns i den typiska storleken hos den region av kvasarer som ger upphov till den optiska och ultravioletta kontinuumstrålningen.

I artikel II undersöker vi om de optiska ljusvariationer som observeras hos kvasarer under tidsskalor av år och decennier kan ha sitt ursprung i mikrolinseffekter. Om så vore fallet, vilket hävdats av Hawkins (1993, 1996, 2000, 2001, 2002), betyder det att en stor del av den mörka materian måste vara i form av kompakta objekt med massor i planetintervallet. Vi visar, i den mest ingående analysen hittills av detta scenario, att även om mikrolinseffekter kan förklara vissa aspekter av ljusvariationerna, så kan de inte förklara alla. Åtminstone vissa av långtidsvariationerna måste alstras av någon annan mekanism. Detta försvårar kraftigt möjligheten att dra slutsatser om den mörka materians egenskaper utifrån de uppmätta ljuskurvorna och ogiltigförklarar Hawkins analys.

Avståndet till kvasarer bestäms normalt genom att mäta deras rödförskjutning. I den rådande kosmologiska modellen uppstod det observerbara universumet i ett s.k. Big Bang för ca 14 miljarder år sedan, och har expanderat sedan dess. Rödförskjutningen är en effekt av universums pågående expansion, som får positionen för emissions- eller absorptionslinjer att förskjutas till längre våglängder från sin förväntade position i det elektromagnetiska spektrumet. Ju avlägsnare ett objekt är, desto mer har universum hunnit expandera under ljusets resa från objektet till oss. Ett mer avlägset objekt uppvisar därför högre rödförskjutning än ett närbeläget. Ända sedan kvasarerna upptäcktes på 1960-talet har det likväl förekommit förslag om att rödförskjutningen hos dessa objekt inte enbart är en effekt av universums expansion, utan att någon annan, okänd mekanism kanske också bidrar. Om detta visade sig stämma skulle möjligheten att använda kvasarer för att säga något om den mörka materian längs synlinjen (som t.ex. i artikel I och II) kraftigt begränsas, eftersom kvasarernas avstånd från oss inte längre skulle vara välbestämt.

Ett kontroversiellt scenario (se t.ex. Arp 1998) som stöds av många förespråkare av s.k. icke-kosmologiska rödförskjutningar (rödförskjutningar som inte är kopplade till universums expansion), är att åtminstone vissa kvasarer kastats ut från de inre delarna av galaxer. Strax efter utkastningen är kvasarernas rödförskjutning hög, för att sedan sjunka till rödförskjutningen hos deras modergalax. I och med att rödförskjutningen sjunker upphör det utkastade föremålet successivt att manifestera sig som en kvasar, och kommer efter tillräckligt lång tid eventuellt att övergå till att bli en helt ny galax. I en modell som lagts fram av Bell (2002) för att förklara positionerna hos kvasarer funna kring galaxen NGC 1068 kommer de utkastade objekten att manifestera sig som kvasarer under mindre än 100 miljoner år. I artikel III beskrivs en möjlighet att falsifiera detta scenario genom att studera den värdgalax som omger normala kvasarer. Om kvasarerna som ingår i de kvasar-galax-associationer som anses utgöra de starkaste stöden för icke-kosmologiska rödförskjutningar också har värdgalaxer – eller något som ens liknar en värdgalax – förväntar man sig i Bells scenario att dessa antingen skall utgöras av stjärnor med åldrar lägre än 100 miljoner år, eller av gas som fotojoniserats av kvasaren. I artikel III visas att båda dessa alternativ skulle leda till egenskaper hos värdgalaxerna som kraftigt skiljer sig från de som hittills observerats. Genom att studera värdgalaxerna hos kvasarerna i de system som anses utgöra de bästa stödet för utkastningshypotesen, bör det alltså vara möjligt att motbevisa den modell för icke-kosmologisk rödförskjutning som framlagts av Bell (2002). I avhandlingssammanfattningen diskuteras även andra metoder för att testa liknande scenarion.

Ytljussvaga galaxer

Ytljussvaga galaxer är galaxer som, i jämförelse med vår egen galax Vintergatan, bildat ovanligt få stjärnor per ytenhet. Eftersom kvoten mellan mörk och ljusstark materia verkar vara högre i de ytljussvaga galaxerna har de länge fungerat som viktiga redskap för att studera den mörka materians egenskaper. Det mesta av den mörka materian tros idag vara av s.k. kall typ (på engelska Cold Dark Matter; CDM), vilket innebär att de mörka partiklarna tidigt i universums historia hade låga hastigheter och främst växelverkar genom gravitationen. Alla galaxer tros vidare vara omgivna av en s.k. mörk halo – en fylld sfär av mörk materia, med både större utsträckning och högre massa än de synliga delarna hos galaxerna. Ett problem med CDM-scenariot som fått stor uppmärksamhet de senaste åren, är att denna modell förutspår en radiell densitetsfördelning i den mörka halon som hittills inte kunnat bekräftas av observationer.

En metod för att mäta den mörka halons densitetsprofil går ut på att mäta rotationshastigheter vid olika avstånd från centrum av skivgalaxer. För att undvika effekterna av ljusstark materia på mätningen bör man välja objekt där det relativa massbidraget från denna är så liten som möjligt. Eftersom ytljussvaga galaxer tros domineras av mörk materia har dessa använts flitigt vid undersökningar av detta slag. Enligt CDM-modellen bör den mörka halon kring en galax uppvisa en kraftig förtätning av mörk materia nära centrum, medan observationer av ytljussvaga galaxer snarare verkar stödja existensen av en kärna av mer eller mindre konstant täthet. För att råda bot på detta har alternativa scenarion, såsom varm, självväxelverkande eller sönderfallande mörk materia föreslagits.

I artikel IV undersöks stjärninnehållet i en klass av särskilt blå ytljussvaga galaxer. I den rådande kosmologiska modellen förutspås galaxer av liknande massa som dessa ha bildats företrädesvis tidigt i Universums historia (2–3 miljarder år efter Big Bang), medan de extremt blå färgerna hos dessa objekt eventuellt kan tolkas som att de bildats relativt sent (kanske så mycket som 13 miljarder år efter Big Bang). Vi visar att problemet med att fastställa åldrarna hos dessa galaxer är avsevärt svårare än vad som tidigare antagits, och att existerande observationer i optiskt och infrarött ljus inte räcker till för att säkert fastslå om de är unga eller gamla. Ytterligare observationer, speciellt från det ultravioletta våglängdsområdet, föreslås för att komma till rätta med problemet. Vi visar också att modeller för ytljussvaga galaxer, som förutspår att gasen i dessa objekt omvandlats till stjärnor i en takt som varit konstant eller ökat sedan deras bildande, inte kan vara korrekta såvida inte kvoten mellan stjärnor av låg och hög massa i dessa galaxer är ovanligt hög. Detta skulle kunna betyda att den sammantagna massan hos stjärnpopulationen i dessa galaxer är avsevärt högre än vad man hittills trott, och att andelen mörk materia i de inre delarna mindre. Om detta visar sig stämma kan flera undersökningar som använt ytljussvaga galaxer för att studera den mörka materians egenskaper komma att måsta omvärderas.

I artikel V presenteras rotationskurvor för sex galaxer med egenskaper liknande de som analyserats i artikel IV. Dessa används för att bestämma egenskaperna hos deras mörka halor. Vi finner inget stöd för någon kraftig densitetshöjning i centrum av det slag som förutspås av CDM, i överensstämmelse med liknande undersökningar för andra typer av ytljussvaga galaxer. Medeltätheten i de inre delarna av just denna typ av ytljussvaga galaxer verkar dock vara lägre än i allmänhet, vilket ställer ovanligt hårda krav på alternativa modeller för den mörka materians egenskaper. Våra observationer verkar även motsäga en nyligen föreslagen modell, som föreslår att densitetshöjningen i centrum skulle ha kunnat jämnas ut genom en tidig kollapsfas i galaxernas utveckling. Givet en viss kosmisk spridning i egenskaperna hos mörka halor kan det dock inte uteslutas att vissa sorters objekt – såsom ytljussvaga galaxer, eller som i detta fall, en särskild undergrupp – företrädesvis bildas i halor med särskilt låg täthet. Detta skulle kunna förklara vissa av skillnaderna mellan CDM-scenariots förutsägelser och observationer av detta slag.

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