Completely dark galaxies: their existence, properties, and strategies for finding them

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ABSTRACT
There are a number of theoretical and observational hints that large numbers of low-mass galaxies composed entirely of dark matter exist in the field. The theoretical considerations follow from the prediction of cold dark matter theory that there exist many low-mass galaxies for every massive one. The observational considerations follow from the observed paucity of these low-mass galaxies in the field but not in dense clusters of galaxies; this suggests that the lack of small galaxies in the field is due to the inhibition of star formation in the galaxies as opposed to the fact that their small dark matter halos do not exist. In this work we outline the likely properties of low-mass dark galaxies, and describe observational strategies for finding them, and where in the sky to search. The results are presented as a function of the global properties of dark matter, in particular the presence or absence of a substantial baryonic dark matter component. If the dark matter is purely cold and has a Navarro, Frenk & White density profile, directly detecting dark galaxies will only be feasible with present technology if the galaxy has a maximum velocity dispersion in excess of 70 km s$^{-1}$, in which case the dark galaxies could strongly lens background objects. This is much higher than the maximum velocity dispersions in most dwarf galaxies. If the dark matter in galaxy halos has a baryonic component close to the cosmic ratio, the possibility of directly detecting dark galaxies is much more realistic; the optimal method of detection will depend on the nature of the dark matter. A number of more indirect methods are also discussed.

Key words: dark matter – cosmology: observations – cosmology: theory

1 INTRODUCTION: EVIDENCE FOR THE EXISTENCE OF DARK GALAXIES
It has been a long-recognized feature of hierarchical clustering models of galaxy formation, like the cold dark matter (CDM) model, that they predict the existence of a very large numbers of low-mass galaxies. This follows directly from the shape of the fluctuation spectrum. On the mass scales that correspond to those of galaxies, cold dark matter has a fluctuation spectrum $\delta(k)$ whose power spectrum $|\delta(k)|^2 \sim k^n$ has index $n \sim -2$ (Bardeen et al. 1986); such a power spectrum results in a mass function of dark-matter (DM) halos that is steep at low masses, close to $n(M) \sim M^{-2}$ (Press & Schechter 1974, White & Rees 1978, White & Frenk 1991, Lee & Shandarin 1999). The prediction of CDM theory that there should exist many satellite galaxies per giant galaxy has recently been confirmed by numerical simulations (Moore et al. 1999, Klypin et al. 1999 and references therein).

But observations (Cowie et al. 1996, Lin et al. 1996, Ellis et al. 1996) show that field galaxies have a luminosity function $n(L)$ far shallower than $n(L) \sim L^{-2}$. This is normally reconciled with a steep mass function by arguing that the formation of stars in low-mass galaxies is inefficient (e.g. Efstathiou 1992, White & Kauffmann 1994, Efstathiou 2000) so that low-mass galaxies have far less luminosity per unit total mass (including dark matter) than high-mass galaxies.

Recent observations have, however, revealed steep luminosity functions $n(L) \sim L^{-2}$ in both the Virgo (Phillipps et al. 1998) and Fornax (Kambas et al. 2000) clusters. Neither of these are particularly rich clusters, like the Coma cluster, but the important thing is that they are (unlike Coma) close enough to us that they are (unlike Coma) close enough to us that their luminosity functions can be measured directly down to very faint limits (see Fig. 2 of Trentham 1998). On the other hand the luminosity function of galaxies in the Ursa Major Cluster (Trentham, Tully & Verheijen 2000), a nearby diffuse group of spiral galaxies about one-twentieth as massive as the Virgo Cluster (Tully et al. 1996), is far shallower than this. The Ursa Major and Virgo/Fornax luminosity functions are inconsistent at a high level of confidence. The advent of mosaic CCDs
on large telescopes and the consequent improved depth to which large areas of the sky can be surveyed to very faint magnitudes (the Trentham et al. (2000) Ursa Major survey had a 1σ surface-brightness threshold fainter than $\mu_R = 27$ mag arcsec$^{-2}$) means that the long-standing worry (Disney 1976) of there existing many galaxies in diffuse environments that are missing from (previously shallow) surveys because their surface-brightnesses are too low is far less serious than it used to be.

It also appears that the luminosity function of the Local Group (van den Bergh 2000 and references therein) is not steep between $M_R = -13$ and $M_R = -11$, which is where the Virgo Cluster luminosity function is found to be steep; galaxies that have been discovered recently in the Local Group, like Cetus (Whiting, Hau & Irwin 1999) are fainter than this, so that van den Bergh’s luminosity function is probably complete down to $M_R = -11$. The shallow luminosity function that was seen in Ursa Major may well therefore be a common feature of diffuse environments. This would be in apparent contrast to the upturn in the luminosity function of dwarf irregular galaxies in the field seen by Marzke et al. (1994), but the value of $\alpha \sim -1.8$ quoted by those authors comes from a Schechter (1976) function fit to the luminosity function and is only very indirectly related to the faint-end power-law index of the luminosity function as discussed above (the Schechter $\alpha$ is determined primarily by the shape of the bright end of the luminosity function appropriate the the particular kind of galaxy being studied; see Section 2 of Trentham 1997)

Let us assume that the mass function of halos is the same in small galaxy clusters like Virgo and Fornax as it is in large galaxy groups like Ursa Major. This would be likely in any hierarchical clustering model of galaxy formation in low-density environments. It would be less true in very high-density environments like the cores of very rich galaxy clusters like Coma where dark-matter halos can be tidally disrupted (see the high-resolution numerical simulations of Giffinga et al. 1998), but in this case the variation of the mass function with density is in the opposite sense to what is observed in Virgo, Fornax, and Ursa Major – namely, small galaxies are rarer in the denser environments. It follows from this assumption about the mass function that there must be many galaxies in the diffuse environments that are completely dark and never formed stars (see also the discussion in Section 5.2 of Klypin et al. 1999).

There could be many reasons for why this happened, like gas availability (Virgo and Fornax have substantial X-ray gas halos so presumably had a reservoir of gas in the past which has since been gravitationally heated — Ursa Major does not) and the tidal creation (Barnes & Hernquist 1992a) and destruction (Putman et al. 1998 and references therein) of dwarfs. The lack of gas availability for low-mass halos in low-density environments may follow from the heating and ionization of the intergalactic medium by OB stars and supernovae over cosmic time (Klypin et al. 1999; Bullock, Kravstov & Weinberg 2000). Whatever the mechanism, it must generate a large effect: there are more than ten times as many $M_R = -11$ dwarfs in Virgo per $M_R = -20$ giant galaxy than in Ursa Major (Phillipps et al. 1998, Trentham et al. 2000). But the existence of large numbers of dark galaxies in the diffuse environments does not depend on the details of this mechanism; it depends only on the assertion that the mass function does not vary. The fact that it is also predicted by CDM theory, and the success of that theory at predicting galaxy properties and large-scale structure on many different scales (e.g. Jenkins et al. 1998; Fontana et al. 1999; Katz, Hernquist & Weinberg 1999; Kauffmann et al, 1999) simply gives additional weight to the hypothesis that these dark galaxies exist. In CDM theories, these dark halos in low density environments will tend to have formed during most of the history of the Universe, except at very early times (then these halos could form stars). They probably are still forming now.

The dark galaxy hypothesis is one way to solve the problem of CDM theories overproducing large numbers of small galaxies without having to abandon the theories and their other successes. An alternative way to perturb the theories so as to avoid this discrepancy is to force the cold dark matter to be self-interacting (Spergel & Steinhardt 2000, Burkert 2000; however see Miralda-Escudé 2000). In this case the mass function of low-mass galaxies in the field is substantially shallower than $n(M) \sim M^{-2}$.

If we accept this possibility of many dark galaxies existing, we can then ask the question: can we find them, and how? This is the subject of the present paper. The optimum methods of searching for dark galaxies depend on the nature of the dark matter, in particular whether or not any of the dark matter is baryonic. The results also depend on the total masses of the dark galaxies, which are unknown. Given the arguments in the previous paragraphs, they will be similar to the total masses of the galaxies that created the upturn in the Virgo luminosity function. These have absolute magnitudes $M_R > -13$, and so have stellar masses of $\lesssim 10^6 M_\odot$ (assuming an R-band stellar mass-to-light ratio of 1). The total masses are therefore likely to be $\lesssim 10^8 M_\odot$, given a cosmic ratio of baryonic matter to dark matter of 0.1 (see Section 2 and references therein) and the fact that the fraction of baryonic matter in galaxies which did form stars is likely to be close to this number or lower; the present-day masses of the Virgo dwarfs may be lower than this due to tidal stripping of their dark matter within the Virgo cluster but here we are concerned with the initial masses of the halos. We therefore restrict the discussion in this paper to dark galaxies with masses $\lesssim 10^8 M_\odot$.

In Section 2 we review current observations that give some constraints on the dark matter composition. In Section 3 we describe ways that dark galaxies can be observed and structure this section according to the possibilities highlighted in Section 2. In Section 4 we discuss further where are the best places in the sky to make the observations described in Section 3. Throughout this work, we assume the following cosmological parameters: $H_0 = 65$ kms$^{-1}$Mpc$^{-1}$, $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$. The majority of the observational tests that we suggest target local dark galaxies and the strategies do not depend significantly on the cosmology.

## 2 PROPERTIES OF DARK GALAXIES

### 2.1 The cold dark matter component

It is well established (e.g. Persic & Salucci 1988, Pryor & Kormendy 1990, Mateo et al. 1993) that dwarf galaxies have very large dark matter fractions. The smallest galaxies
known (Draco and Ursa Minor) are at least 99 per cent dark matter by mass (Pryor & Kormendy 1990).

These very high dark matter fractions probably result from baryonic blowout caused by supernova-driven winds from the few high-mass stars that formed early in the history of the galaxy (Dehnen & Silk 1996). Although the light profiles for very low-luminosity galaxies are reasonably well determined, the dark matter profiles are poorly constrained by observation since the dark matter extends well beyond the observed stars so that no tracers of the mass are available (see Pryor & Kormendy (1990) and Mateo et al. (1993) for some models).

So there is very little direct information about the distribution of dark matter in the smallest galaxies. Most of the dark matter is presumably normal cold dark matter, with global ratios of cold to baryonic matter equal to or less than the cosmic ratio (about one-tenth, from a comparison of the cosmic total mass density $\Omega \sim 0.3$ e.g. Perlmutter et al. 1999 to the baryonic mass density $\Omega_\text{b} \sim 0.03$ e.g. Smith et al. 1993). The dark galaxies that we study in the current paper are the (more common) analogues of these low luminosity galaxies, these being the ones that never made any stars at all. So the profile of CDM in these completely dark galaxies is difficult to estimate. A reasonable possibility is that the CDM component will have a density profile close to a Navarro, Frenk & White (1996, 1997; hereafter NFW) one, assuming that the scaling relations derived by those authors from simulations of much larger bound systems are valid for low-mass ones. Recall that CDM theory and the observed absence of low-luminosity galaxies in diffuse environments were the main motivations for hypothesizing the existence of such galaxies, and these in conjunction would suggest that a NFW density profile would be suitable for the cold dark matter, particularly if the baryonic contribution to the dark matter is small.

2.2 The baryonic component

However, the dark matter component might not be purely CDM and there might be a baryonic component. If this is true in dark galaxies, there are important implications for detectability.

One piece of evidence that baryonic dark matter exists is that some galaxies have density profiles inferred from rotation curves that are not consistent with extrapolations of the NFW profile to lower mass systems (Moore 1994, Burkert & Silk 1997, Navarro & Steinmetz 2000). The Milky Way, for example, has less mass interior to the solar circle than predicted from an NFW profile (Navarro & Steinmetz 2000); its density profile is shallower than $r^{-1}$. The case of the dwarf spiral DDO 154 is studied in particular detail by Burkert & Silk (1997). As these authors point out, a high baryonic dark matter fraction (50 per cent, far in excess of the global value of 6.5 per cent derived by Hernandez & Gilmore 1998) can alleviate this problem. Another way to solve the problem is to force the CDM to be self-interacting, as outlined in the previous section (Spergel & Steinhardt 2000). However, systematic observational effects (e.g. beam smearing) may themselves be the source the problem. Indeed, van den Bosch & Swaters (2000) show that when the effects of beam smearing and the physics of adiabatic contraction are taken into account, the mass models permitted by the rotation curves of dwarf spiral galaxies are consistent with CDM theory (see also the discussion in Flores & Primack 1994).

Another piece of evidence that baryonic dark matter exists is the cosmic baryonic budget of Fukugita, Hogan & Peebles (1998). These authors cannot account for more than about 20 per cent of baryons in the Universe (as inferred from Big Bang nucleosynthesis) in stars and gas. Some of the missing baryons may be in a form that is dark, and could account for some fraction of the dark matter in the kind of halos we are looking for. If this is the case, however, dark matter that resides in small galaxies probably cannot form a major part of the missing baryons, since the cosmological density residing in baryons in the high-redshift intergalactic medium is close to the nucleosynthesis value (Weinberg et al. 1997), and it is difficult to see how hot gas like this can condense into the small halos, particularly in light of the rationale in Section 1 as to why the galaxies are dark. However, some small fraction of the missing baryons could certainly be associated with small CDM halos.

In the rest of this section we consider some possible forms which this baryonic dark matter might take.

2.2.1 Brown dwarfs

Brown dwarfs are stars with masses lower than the hydrogen-burning limit of 0.08 $M_\odot$. They are not a significant contributor to the mass in young star-forming regions like the Pleiades (Hodgkin & Jameson 2000). In addition, they are probably not a major component of the dark mass in the outer parts of the Milky Way, as inferred from the MACHO (Alcock et al. 2000) and EROS (Afonso et al. 1998) microlensing experiments. In addition to generating microlensing effects, brown dwarfs emit thermal radiation at mid-infrared wavelengths and can be detected this way. In the external spiral galaxy NGC 4565 (Beichman et al. 1999), there are constraints from ISO, but they do not rule out the possibility of a significant fraction of dark matter being brown dwarfs. In dwarf spiral galaxies the ISO measurements (Gilmore & Unavane 1998) are also unable to rule out a significant fraction of dark matter (inferred to exist from rotation curves) from being in the form of brown dwarfs. For a review of the plausibility of brown dwarfs as dark matter, see Gilmore (1999).

In the lowest mass galaxies, many of which may be completely dark, let us hypothesize that some of the dark matter may be brown dwarfs. Even if the fraction of the dark matter in this form only is a few per cent, this hypothesis would require that they formed with a very different stellar mass function (IMF) than that appropriate for the solar neighbourhood (e.g. Kroupa, Tout & Gilmore 1993). This discrepancy follows from the paucity of normal stars in dark galaxies. This assertion is somewhat unattractive because the solar-neighbourhood IMF seems be universal wherever direct observations may be made, in both Population I and Population II environments (Gilmore & Howell 1998). On the other hand, the brown dwarfs that we consider here may be Population III objects, and a different IMF for Population III stars could result from a variety of physical processes e.g. the molecular hydrogen out of which the stars formed was generated in a different way, probably by triple-H collisions (Palla, Salpeter & Stahler 1983), since no dust grains existed (adsorption of H atoms onto dust is the most effi-
efficient way of making molecular hydrogen in Population I and probably Population II environments).

2.2.2 Molecular hydrogen

Molecular hydrogen (H$_2$), if pristine and not contaminated with dust (which can be seen with submillimetre bolometers and CO line receivers) is notoriously difficult to detect (Combes & Pfenniger 1997). Pfenniger, Combes & Martinet (1994) argue that unenriched molecular gas could be a common form of halo dark matter in giant galaxies. The main arguments against these clouds being the predominant form of halo dark matter are mainly cosmological: (i) the cosmological density of dark matter is a factor of several higher than the cosmological density of baryons, as outlined in Section 2.1, and (ii) these clouds cannot survive at high redshift where the temperature of the microwave background is higher (Wardle & Walker 1999), so their formation has to be finely tuned to happen at low redshift, well after the bulk of star formation in the Universe (Madau et al. 1996). But there is nothing to suggest that small clumps of molecular hydrogen cannot exist as trace amounts of dark matter in late-forming galaxies. Such clouds are thermally stable (Wardle & Walker 1999). If such clouds exist in dark galaxies, they might help the galaxies be detected, for example by increasing the angular extent of the galaxy that has a surface density higher than the critical density for strong lensing (see Section 3.1).

2.2.3 Stellar remnants

Two kinds of stellar remnants could contribute at some level to the dark matter: compact objects like neutron stars and black holes, and cold white dwarfs.

Early supernovae will leave remnants with kick velocities in excess of the escape velocities of the galaxies. Pulsar birth speeds in the Galaxy are typically in excess of 200 km s$^{-1}$ (Lyne & Lorimer 1994, Hansen & Phinney 1997). The escape velocities of the small galaxies which are hypothesized to form stars in the very early Universe are small (< 200 km s$^{-1}$) since big galaxies with deep gravitational potential wells have not yet had time to form (see Tegmark et al. 1997 for a description of the formation of the very first galaxies and the relevant mass scales, and Gnedin & Ostriker 1997 for a cosmological simulation of the early formation of galaxies; note that the escape velocity of a virialized galaxy is approximately twice the velocity dispersion – e.g. p. 119 of Saslaw 2000). If the physics of core-collapse supernovae is invariant with cosmic time, early-forming remnants will therefore leave the parent galaxies and intergalactic space may contain many such objects. It is therefore possible that later-forming dark matter halos of the type described in Section 1 may accrete a handful of these remnants. They could therefore be present in trace amounts in dark galaxies.

One interesting recent result is the detection of three cold (< 4000 K), and therefore extremely old, white dwarfs (CWDs) in the Milky Way halo (Hambly, Smartt & Hodgkin 1997, Harris et al. 1999, Ibata et al. 2000). These have spectral energy distributions that peak at about 1 µm (Hodgkin et al. 2000) due to molecular collision-induced absorption at longer wavelengths (Hansen 1999). They are, however, very faint ($M_V \sim 17$, V-band mass-to-light ration $= 5 \times 10^4$ in solar units) and so are almost dark. The presence of even these three objects given the selection effects appropriate to the above surveys implies the existence of massive progenitors that are sufficiently numerous that they are not consistent with an extrapolation of the normal halo population to higher masses, given a normal stellar IMF like that of Kroupa et al. (1993). These progenitors could be Population III objects. No abundances are known for the CWDs, since no metals are present in their atmospheres; the metallicities of their progenitors are therefore unconstrained. The CWDs may be associated with very early formation of the Milky Way (i.e. at times before the normal halo population and globular clusters formed). Alternatively they could have been accreted by the Milky Way halo from intergalactic space if they formed in fragile small galaxies in the early Universe which had been tidally disrupted. The latter is suggested by the fact that a substantial population of old white dwarfs forming within the Milky Way halo would have resulted in too much heavy element production (see Gilmore & Unavane 1998 and references therein; also Gilmore 1999). The comments made in Section 2.2.1 about the plausibility of Population III having an IMF that is different from Populations I and II is valid here too, although it would be in the opposite sense to the difference hypothesized in that section i.e. skewed towards high, not low, masses.

3 TECHNIQUES FOR FINDING DARK GALAXIES

3.1 Gravitational lensing

In this section we assess under what conditions a dark galaxy could be detected through gravitational lensing of background sources.

3.1.1 Strong lensing by dark halos

Following Section 2.1, let us assume that the dark matter density has a NFW (Navarro, Frenk & White 1996, 1997) profile:

$$\rho(r) = \frac{\rho_0}{(r/r_s)(1 + r/r_s)^2}$$  (1)

where the scale density $\rho_0$ and radius $r_s$ are determined uniquely by two free parameters of the halo, in the current work chosen to be the virial mass $M_V$ and maximum velocity dispersion $\sigma_{\text{max}}$. If we fix $M_V$ and $\sigma_{\text{max}}$, then $\rho_0$, $r_s$ and a concentration index $C$ are uniquely defined by the equations

$$\rho_0 = 3.6 \times 10^6 \left( \frac{\sigma_{\text{max}}}{100\text{ km s}^{-1}} \right)^6 \left( \frac{M_V}{10^{11} M_\odot} \right)^{-2} \times \left( \ln(1 + C) - C/(1 + C) \right)^2 M_\odot \text{kpc}^{-3};$$  (2)

$$r_s = 2.8 \left( \frac{M_V}{10^{11} M_\odot} \right) \left( \frac{\sigma_{\text{max}}}{100\text{ km s}^{-1}} \right)^2 \times \left( \ln(1 + C) - C/(1 + C) \right)^{-1} \text{kpc};$$  (3)

$$r_s = \frac{1}{C} \left( \frac{3M_V}{800\rho_0 \sigma_{\text{max}}} \right)^{1/3}. $$  (4)
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Figure 1. Einstein radii for NFW lenses at various distances. The NFW profiles are chosen according to their virial masses $M_V$ and maximum velocity dispersion $\sigma_{\text{max}}$. In all panels the different lines represent lenses of different mass: $M_V = 10^7 M_\odot$ – solid line; $M_V = 10^8 M_\odot$ – short dashed line; $M_V = 10^9 M_\odot$ – long dashed line; $M_V = 10^{10} M_\odot$ – dotted-dashed line. The different panels are for halos of different $\sigma_{\text{max}}$, as shown. By “small” $\sigma_{\text{max}}$ we mean $1.9 \text{ km s}^{-1}$ ($M_V = 10^7 M_\odot$), $4.1 \text{ km s}^{-1}$ ($M_V = 10^8 M_\odot$), $8.6 \text{ km s}^{-1}$ ($M_V = 10^9 M_\odot$), or $18.1 \text{ km s}^{-1}$ ($M_V = 10^{10} M_\odot$).

Here $\rho_c$ is the critical density of the Universe (throughout this section we assume the redshift $z = 0$).

The radius of the tangential critical curve of an axially symmetric lens (the Einstein radius) is equal to the radial distance at which the mean surface density within that radius equals the critical surface density for strong lensing (Schneider, Ehlers & Falco 1992, p. 233). The mean surface mass density $\bar{\Sigma}$ at distances $r = r_s x$ is given by

$$\bar{\Sigma} = 4 r_s \rho_0 \times f(x),$$

where the function

$$f(x) = \begin{cases} \frac{1}{x^2} \left( \frac{2}{\sqrt{1-x^2}} \arctanh \sqrt{\frac{1-x}{1+x}} + \ln(x/2) \right) & : x < 1 \\ 1 + \ln(1/2) & : x = 1 \\ \frac{1}{x^2} \left( \frac{2}{\sqrt{x^2-1}} \arctan \sqrt{\frac{1-x}{1+x}} + \ln(x/2) \right) & : x > 1 \end{cases}$$

The Einstein radius is then the radius of that circular region in which $\bar{\Sigma} = \Sigma_c(z_l, z_s)$ where $\Sigma_c$ is the critical density for lens redshift $z_l$ and source redshift $z_s$. For nearby lenses at distance $D$ such that $z \ll 1$, and sources at cosmological distances, the critical density is

$$\Sigma_c = \frac{c^2}{4\pi GD}$$

where $c$ is the speed of light and $G$ is the gravitational constant. If we now set $M_V$ and $\sigma_{\text{max}}$ for NFW lenses and place them at distance $D$, we can work out the Einstein radii for these lenses. This is done in Figure 1.

Radio VLBI interferometry can achieve an angular resolution of about $10^{-4}$ arcsec. This is the best resolution available for radioastronomy until space interferometers are deployed. From Fig. 1, dark galaxies with $\sigma_{\text{max}} > 70 \text{ km s}^{-1}$...
at distances greater than 10 Mpc could strongly lens background quasars and generate multiple images with separations that could be detected by VLBI interferometry. The number of such objects that we might expect to find depends on the fraction of low-mass dark galaxies with \( \sigma_{\text{max}} > 70 \text{ km s}^{-1} \). Unfortunately this velocity is high, larger than the maximum velocity dispersion of dwarf spiral galaxies like DDO 154 (Burkert & Silk 1997) and much larger than the velocity dispersions of the dwarf elliptical galaxies studied by Kormendy (1987), thought to be the counterparts of the dark galaxies which \textit{did} make stars. It is therefore not surprising that to date no lens system where the lens is dark has been detected with VLBI.

The detectability of dark galaxies through strong gravitational lensing becomes much higher if some fraction of the dark matter is very compact and does not follow a NFW profile, say in a supermassive black hole at the galaxy center. For a point mass \( M \) at distance \( D \), the Einstein radius for sources at cosmological distances is

\[
\theta_E = 0.029 \left( \frac{M}{10^8 M_\odot} \right)^{0.5} \left( \frac{D}{10 \text{ Mpc}} \right)^{-0.5} \text{arcsec},
\]

which is 0.029 arcseconds for masses of \( 10^6 M_\odot \), easily detectable with current radio telescopes. There is, however, no evidence that low-luminosity late-type galaxies (the visible counterparts of the dark galaxies) have central mass concentrations this large (Kormendy & Richstone 1995). We therefore do not expect the kind of dark galaxies that we hypothesise here to have them either. If the NFW density profile can indeed be extrapolated to low masses for galaxies composed almost entirely of CDM, the only circumstances where this might be a realistic possibility is if dark galaxies have dense baryonic cores (for example, these could be made of molecular gas that somehow never made stars, as argued in Section 2.2.2).

### 3.1.2 Weak lensing by dark halos

The previous analysis has concentrated on strong lensing. But if dark halos are present in enough number, their cumulative weak lensing effects might be measurable.

In a recent paper, Natarajan & Kneib (1997) showed how the granularity in the shear map of a galaxy cluster could be used to infer the presence of dark halos around individual galaxies. With current data, this method can only be used to look for massive (> \( 10^{10} M_\odot \)) halos in distant, rich clusters with small angular extent on the sky, due to shot noise limitations. However, if it is possible at some time in the future to image very deeply over large angular areas of the sky at high resolution (say, with an array of telescopes using orthogonal transfer CCDs; Kaiser, Tonry & Luppino 2000), then it should be possible to apply the analysis of Natarajan & Kneib to more diffuse, spiral-rich groups of galaxies to look for massive dark halos. These environments would be particularly suitable for such an analysis since (i) they are dynamically unevolved, and so likely to have many dark halos based on the arguments in Section 1, and (ii) they do not have substantial dense dark matter concentrations associated with the overall structure as opposed to individual galaxies (as do rich clusters), small pieces of which could be tidally torn off and mimic dark galaxies.

### 3.1.3 Strong lensing by individual brown dwarfs or stellar remnants

We have argued in the previous section that it is possible that dark galaxies may have some brown dwarfs or stellar remnants associated with them. These could be responsible for microlensing events, like those of Magellanic Cloud stars observed by the MACHO and EROS collaborations. A large number of such events from a small angular region of the sky may indicate the presence of an anomalously large number of brown dwarfs or stellar remnants that are very close in physical space. If these are not so close as to be self-gravitating, they could signify the existence of a dark satellite somewhere between us and the Magellanic Cloud. See Widrow & Dubinski (1999) for a detailed simulation-based treatment of this phenomenon.

The non-detection of such a phenomenon so far places a limit on the joint density of dark satellites around the Milky Way and the contribution of brown dwarfs and stellar remnants to their total masses. Unfortunately, the angular area of the sky probed by the above experiments combined with the predicted number density of dark satellites (about \( 10^7 \) in the entire Local Group; see Klypin et al. 1999 – the volume of the cone subtended by the Magellanic Cloud to an observer on Earth is only about \( 10^{-7} \) of the volume of the Local Group) means that this constraint is not strong.

### 3.2 Infrared radiation

#### 3.2.1 Mid-infrared Thermal Radiation from Brown Dwarfs

If a significant fraction of the dark matter in dark galaxies is in the form of brown dwarfs, as highlighted in Section 2.2.1, these may be detectable at mid-infrared (5 \( \mu m \) – 30 \( \mu m \)) wavelengths. They therefore may offer one potential way to directly see an otherwise dark galaxy. Gilmore & Unavane (1998) placed upper limits on the number of brown dwarfs in a sample of dwarf spiral galaxies using ISO observations at 7 \( \mu m \) and 15 \( \mu m \). With the next generation of mid-infrared space observatories and infrared cameras, like SIRTF-MIPS, far more sensitive observations will be possible. The following quantitative analysis is based on the strategy adopted by Gilmore & Unavane for their ISO observations.

Brown dwarfs have spectral energy distributions that peak at mid-infrared wavelengths, since (assuming they have low metallicities as would be appropriate for early-forming, or Population III objects) they radiate as cool blackbodies (see Figure 2). A dark galaxy may consist of a population of such objects (in the analysis below we assume that they all the same mass and age). For a spherical brown dwarf population with projected density profile \( \Sigma(\theta) \), the flux density emitted per unit angular area from an element at angular distance \( \theta \) from the center is

\[
I(\theta) = 0.0145 M_\odot v_{14}^3 I^{-0.01} m^{-2.66} D_I^{-2} \times \left( \exp \left( 0.278 v_{14} t^{0.31} m^{-0.79} \right) - 1 \right)^{-1} I(\theta) \text{ mJy rad}^{-2},
\]

where

\[
I(\theta) = \frac{\Sigma(\theta)}{\int_0^\theta \Sigma(\theta) d\theta}.
\]

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Whether or not such a population of brown dwarfs is detectable with an instrument like SIRTF-MIPS (http://ipac.caltech.edu/sirtf/) depends on two issues: (i) the instrument sensitivity, and (ii) the flat-fielding capability. Suppose we want to look for a dark galaxy at a distance of 1 Mpc consisting of $10^8 M_\odot$ (i.e. 10 per cent of a galaxy with total mass $10^9 M_\odot$) of low-metallicity brown dwarfs, each having mass 0.04M_\odot and age 15 Gyr. From Fig. 2, the optimal wavelength to observe is about 25 \mu m, so a suitable instrument to use is SIRTF-MIPS with a 24-\mu m filter. For this instrumental configuration, the beam area is 0.01 arcmin^2 (Blain 1999). From Equation XXX, the total flux in the galaxy seen through this filter is 0.23 mJy. If we assume a projected density profile for the brown dwarfs that is exponential with scale-length 0.1 kpc (this is the scale-length of visible matter in the smallest dwarf elliptical studied by Kormendy 1987), the total flux in a beam centered on the galaxy center is 0.013 mJy. The noise equivalent flux density (NEFD) for this instrumental configuration is 1.8 mJy Hz^{-1/2} (Blain 1999), so a 3\sigma detection could be obtained with an integration time of 200 ks, or about 2.3 days. Probably a somewhat lower integration time can be used if we sum the contributions from several beams centered on the galaxy center; the optimal strategy will depend on the detailed density profile. The second issue we need to consider is the flat-fielding capability of the instrument.

Here $m$ is the mass of the brown dwarfs in $M_\odot$, $t$ is the age of the population in units of Gyr, $M_\ast$ is the total population mass in units of $10^8 M_\odot$, $D_\ast$ is the distance to the galaxy in units of 1 Mpc and $\nu_{14}$ is the frequency in units of $10^{14}$ Hz. The scaling relations of Stevenson (1986) are assumed.

For SIRTF-MIPS operating at 24 \mu m, the field of view is about 5 arcminutes x 5 arcminutes (Blain 1999), about 14.5 scale-lengths for the object above. The numbers above assume perfect flatfielding, and systematic variations in the sensitivity of the detector would need to be accurately corrected for if such a measurement is to be feasible. This would be even more important if we tried to identify dwarfs with $D_\ast < 1$ this way.

The integration time required to achieve a given signal-to-noise scales as $I_\nu^{-2} \sim M_{\ast}^{-2}$, so less substantial populations of these brown dwarfs could be only detected with SIRTF-MIPS if very long integrations are used. Future generations of observatories will, however, have lower NEFDs, as instrument sensitivities improve, and this kind of project becomes feasible even for very trace populations. Dark galaxies would be particularly straightforward objects to observe this way since there is no contamination from long-wavelength emission from normal stars and their debris.

### 3.2.2 Near-Infrared Radiation from Cold White Dwarfs

Cold white dwarfs have spectral energy distributions that peak at about 1 \mu m (Hodgkin et al. 2000) so that a pop-

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**Figure 2.** Contours of wavelength in \mu m at which the maximum flux density is emitted for brown dwarfs of various ages and temperatures. The scaling relations of Stevenson (1986) are used and the brown dwarfs are assumed to radiate as blackbodies, as is appropriate for low metallicities given the more detailed analyses of Burrows et al. (1997) and Baraffe & Allard (1997; see the discussion in Section 6.2.5 of Gilmore & Unavane 1998).

**Figure 3.** A $J - K$ vs. $B - V$ colour-colour diagram showing the location of WD 0346+246 (the star) relative to various low surface-brightness stellar systems (the filled circles) that might mimic a diffuse population of cold white dwarfs in an otherwise dark galaxy. These are (in order of increasing $B - V$): ESO 462–36 (a blue low surface-brightness star-forming galaxy), NGC 4472 dW10 (a blue Virgo dwarf elliptical galaxy) and NGC 4472 dW8 (a red Virgo dwarf elliptical galaxy). The photometry is from Hodgkin et al. (2000) for WD 0346+246, from Bergvall et al. (1999) for ESO 462–36 and from Caldwell (1983) and Bothun & Caldwell (1984) for the Virgo dwarfs. The thin solid line represents the colours for a stellar population generated in an instantaneous starburst seen at times $10^7$ to $2 \times 10^9$ years after the burst, assuming a Miller-Scalo stellar IMF and a metallicity of 1/50 solar, from the models of Bruzual & Charlot (1993). This would be appropriate for a pristine star-forming HII galaxy like 1 Zw 18 (e.g. Hunter & Thronson 1995). The thick solid line represents the colours for a continuously-forming stellar population of solar metallicity, from the same models. The dashed line represents a blackbody.
ulation of such objects could be detected as a faint excess above the sky in J-band (1.25 μm). Such a population could readily be distinguished from other low surface-brightness stellar systems on the basis of their optical+near-infrared colors (see Figure 3). Imagine now an object containing 10⁸ M☉ of CWDs with an exponential mass profile with scale-length h. If placed at a distance of 1 Mpc, such an object will have a J-band surface-brightness profile
\[
\mu_J(\theta) = 33.47 + 5 \log_{10} \left( \frac{h}{1 \text{ kpc}} \right) + 0.00525 \left( \frac{\theta}{1 \text{ arcsec}} \right)^{-1} \text{mag arcsec}^{-2},
\]
which is everywhere much less than the sky surface-brightness in J-band (about 16 J mag arcsec⁻²; Tokunaga 2000). This calculation is based on the spectral energy distribution of WD 0346+246, which has an absolute J-band magnitude of M_J = 17.60 – 5 log_{10}(28/10) = 15.36 and a mass of 0.65 M☉ (Hodgkin et al. 2000).

Such an object would require very long integration times to detect with current telescopes and instruments. For example, in order to get a 3σ detection using the INGRID imaging camera on the 4.2 m William Herschel Telescope (http://www.ast.cam.ac.uk/ING/Astronomy/instruments/ingrid/index.html), an integration of 24 ks (about 0.3 days) is required if h = 0.01 kpc. Additionally, since we are looking for such faint, extended objects, it is important that the images be flatfielded to very high accuracy. Integration times scale as h, so more diffuse populations will be much more difficult to detect. For objects much fainter than the sky, integration times scale as telescope diameter D⁻², so going to larger telescopes helps a little, but very long integrations indeed are still required if h is large. Since part of the motivation for suggesting that some of the dark matter is baryonic in the first place was that luminous dwarf galaxies have constant density cores (i.e. large h), this would seem to suggest that looking for populations of CWDs like this will not be productive. It is only if they have very centrally peaked mass profiles that we will see them, but if such an object is detected we have the advantage of unambiguously knowing what it is given the very substantial difference in colors between WD0346+246 and other stellar systems, as shown on Figure 2.

### 3.3 Gamma-ray burst afterglows and host galaxies

One of the favored theories for the formation of gamma ray bursts (GRBs) is the merger of compact stellar remnants like neutron stars or black holes (Narayan, Paczyński & Piran 1992). Therefore if two of the remnants (accreted by a single dark galaxy as described in Section 2.2.3) happen to merge, then a GRB may result.

The interaction between the burst and the surrounding material results in an afterglow at lower energies (Mészáros and Rees 1998, Böttcher et al. 1999). The properties of this afterglow depend on the density of the ambient medium, which would be far lower in a dark galaxy than in a normal star-forming galaxy, by several orders of magnitude. Thus in principle a GRB occurring in a dark galaxy could be identified as follows. The beginning of the afterglow phase (Vieiti 2000) occurs a time τ_d after the end of the γ-ray emission, where
\[
τ_d \approx 15 \left( \frac{E}{10^{53} \text{erg}} \right)^{1/3} \left( \frac{n}{1 \text{ cm}^{-3}} \right)^{-1/3} \left( \frac{\Gamma}{300} \right)^{-8/3} \text{ s.} \quad (11)
\]
Here n is the density of surrounding matter, E is the total explosion energy of the burst and Γ the initial bulk Lorentz factor. In dark galaxies n is unlikely to be much more than the intergalactic medium value, but in normal galaxies it will probably be close to the the value appropriate to star-forming regions, particularly if most GRBs arise from collapsars (Woosley 1993, Paczyński 1998). Hence GRBs with very large values of τ_d might suggest that the host galaxy is dark. The dependence of τ_d on n¹/³ suggests that any difference in τ_d due to n can be mimicked by a small change in Γ. But the plausible range of Γ (Γ > 30 – Mészáros, Laguna & Rees 1993 – and Γ < 1000 – Ramirez-Ruiz & Fenimore 2000) is so small compared with the plausible range of n (n ≤ 10⁻⁷ cm⁻³ in the IGM, assuming a maximal value from Big Bang Nucleosynthesis – Smith et al. (1993) — and n > 300 cm⁻³ in star-forming molecular clouds – Sanders, Scoville & Solomon 1985) that the two parameters may be individually determined by considering the peak frequency (Wijers et al. 1999)

\[
ν_m \sim 3 \times 10^{15} \left( \frac{1+z}{2} \right)^{1/2} \left( \frac{E}{10^{53} \text{erg}} \right) ^{1/2} \left( \frac{t_{\text{day}}}{15 \text{ s}} \right)^{3/2} \text{ Hz} \quad (12)
\]
and intensity at ν_m (Waxman 1997a,b, Vietri 2000)

\[
F(ν_m) \sim 10 C(z) \left( \frac{n}{1 \text{ cm}^{-3}} \right)^{1/2} \left( \frac{E}{10^{53} \text{erg}} \right)^{1/2} \text{ mJy} \quad (13)
\]

of the afterglow, where t_{day} is the time of observations in units of days since the onset of the afterglow and C(z) is given by

\[
C(z) = \frac{2}{1+z} \left( 1 - \sqrt{1+z} \right)^2. \quad (14)
\]

Here z is the redshift of the burst. A large number of GRBs whose afterglows suggest values of n appropriate to the intergalactic medium value might suggest a substantial population of dark galaxies. No host galaxy should be detectable from any of these events, even with the next generation of extremely large telescopes or the Next Generation Space Telescope (NGST; http://www.ngst.stsci.edu).

### 3.4 Atomic hydrogen searches

Dark halos may over cosmic time have collected small amounts of gas which is cold and in atomic form (HI) to-
be the observational counterparts of the dark galaxies predicted by CDM theory. The dark halos that happen to lie in those environments where there is plenty of gas available could accrete substantial amounts of this gas. This notion is consistent with the observed phenomena that (i) HVCs tend to be found concentrated around the Magellanic Stream where there certainly is a substantial gas reservoir, and (ii) the gas in HVCs is reasonably enriched (0.1 solar; Wakker et al. 1999), and must have experienced chemical evolution somewhere at some time in the past. While intriguing, the interpretation of the HVCs as the observational counterparts of the dark galaxies is still premature. As Klypin et al. (1999) point out in the last paragraph of their Section 5.1, this assertion relies on many observational parameters yet to be determined, but whose measurement is feasible with current technology (e.g. Gibson & Wakker 1999). Two issues that seem particularly important to establish are:

1. that many HVCs can exist at large distance from the Milky Way, so that they are not just a local phenomenon, and

2. the radial metallicity distribution. If HVCs far away from the Milky Way are found to have unenriched gas that is likely pristine (like I Zw 18, or maybe even more unenriched), this would also support the picture that there exist a large number of primordial HVCs unassociated with larger galaxies.

More generally, it seems a good idea to search for small HI systems. Unfortunately, if the column densities of such systems are very low, they cannot be seen in emission without very long integrations due to the noise properties inherent in HI measurements (Disney & Banks 1997; Taylor et al. 1995). Both HI (Taylor et al. 1995) and optical (Telles & Madrazo et al. 2000) analyses show that although a handful of HII galaxies currently the most precisely-determined distances come from parallax measurements with the Hipparcos satellite (http://astro.estec.esa.nl/Hipparcos/), which can determine parallaxes for stars with $B < 9$ to an accuracy of about 0.002 arcseconds. This satellite could therefore only be used to find such associations within 50 pc or so of us i.e. very nearby. Associations more distant than this will have stars too faint to allow accurate parallax measurements, so their distances cannot be determined.

In the future, however, much bigger volumes can be surveyed with the GAIA satellite (http://astro.estec.esa.nl/GAIA/Science/), which will have improvements of factors of 100 in accuracy and 1000 in limiting magnitude over Hipparcos (http://astro.estec.esa.nl/GAIA/Science/Science.html). Anomalous associations of solar-type stars will then be detectable out to 1.7 kpc since the sensitivity of the GAIA parallax measurements will be good enough to determine the distances of stars this far away given their apparent magnitudes. Such stars ($B < 17$) would easily be bright enough for precise velocity dispersion measurements.

3.6 Summary

If dark galaxies contain only, CDM then strong gravitational lensing (Section 3.1.1) is required for a direct detection unless there is a fortuitous discovery of an anomalous stellar association (Section 3.5). If the dark galaxies have NFW density profiles, then strong lensing measurements will, however, be extremely difficult. More likely, indirect methods (Sections 3.1.2, 3.1.3, 3.3 or 3.4) are required. If some small fraction of the dark matter is baryonic, then far-infrared (Section 3.2.1) or near-infrared (Section 3.2.2) searches may be productive if the dark matter is brown dwarfs or CWDs, respectively, although in the latter case the CWDs would need to be fairly concentrated near the galaxy centers.

4 WHERE TO LOOK FOR DARK GALAXIES

For the direct (gravitational lens and infrared search) methods outlined in previous section, it is clear that detecting dark galaxies with present technology is marginal at best. This means that any such observations are best performed by concentrating on a small number specific target fields for which there is a high probability of a dark galaxy existing. We suggest the following possibilities.

4.1 Blue compact dwarf and isolated HII galaxy fields

Blue compact dwarfs (BCDs) and low-luminosity HII starburst galaxies are small galaxies which are undergoing a sudden burst of star formation. They often have very disturbed morphology; a prototype is UGC 6456 (see Lyndes et al. 1998 for an optical HST image). They typically have star formation rates so high that they could not have maintained them for any considerable time or else they would have a total mass in stars higher than is permitted given their total optical luminosity.

Something must have triggered these objects into bursting. Both HI (Taylor et al. 1995) and optical (Telles & Madrazo 2000) analyses show that although a handful of HII
galaxies have companions, most appear to be quite isolated. The analysis of Telles & Maddox (2000) in particular probes down to very faint limits. Their results suggest that something other than an interaction with a normal luminous galaxy is responsible for triggering these isolated HII galaxies into bursting. One possibility is an interaction with a dark galaxy that neither they nor Taylor et al. see because it has too little or no stars or gas. Such a dark galaxy will have gravitational effects that mimic the effects of the companion in the few cases where the HII galaxies does have one. Therefore fields around isolated BCDs and HII galaxies would appear to be good target fields.

4.2 Cores of poor clusters of galaxies

An environment where many dark galaxies probably exist is in the cores of poor, dynamically unevolved clusters. This is because the small halos there have not been able to form stars, for the reasons given in Section 1, yet the overall density (as inferred by the luminous galaxy density and/or dynamical considerations) is high enough that the number density of small halos will not be extremely small. The Ursa Major Cluster is a good example of such an environment, particularly since deep optical observations (Trentham et al. 2000) show that dwarf galaxies of the type that are so numerous in Virgo (Phillipps et al. 1998) do not exist here, despite the cluster being only one-twentieth as massive as Virgo (Tully et al. 1996).

These ideas can be combined with those in the previous section. We therefore suggest that some of the best fields of all to target are fields in the vicinity of starbursting dwarf galaxies in the centers of poor clusters. The field around the BCD galaxy umd 38 (Trentham et al. 2000) in the center of the Ursa Major Cluster is a particularly good example.

4.3 Outflows from isolated galaxies

Interacting galaxy systems are common (see e.g. The Atlas of Peculiar Galaxies; Arp 1966), and often show evidence for material flowing between galaxies. A rarer phenomenon is material flowing out of a galaxy towards apparently nothing. The outflow from UGC 10214 (see Figure 4) is a good example. It is possible that material is being gravitationally pulled out of the galaxy by a dark companion, just like material is pulled out of one member in a more normal interacting system by another member. We therefore suggest that the areas of the sky at the far end of the streams from the host galaxies in systems like this would also be good target fields.

4.4 Fields of dwarf galaxies with anomalous velocities

Some small galaxies have velocities that are difficult to explain given their location in space. An example is Leo I, which is close to the Milky Way Galaxy (MWG) but has an anomalously large velocity with respect to the MWG (Zaritsky, et al. 1989, Byrd et al. 1994). It is probably different from the other Galactic satellites in that it is not orbiting the MWG.

One possibility is that Leo I was orbiting the MWG at some time in the past but recently received a velocity kick from a dark companion that we do not see. If we could identify where in the sky such a companion might be, this might be a reasonable target field for an infrared search for dark galaxies of the type described in the previous section. The region of the sky where such a companion could reside is not large since tidal torques are a rapidly-falling (∼ r⁻³) function of distance; a hypothetical dark companion must therefore be very close to Leo I. Leo I is just one example. As optical spectroscopic surveys get more sensitive, perhaps similar objects (low-mass galaxies are best since they experience greater accelerations for torques of a given magnitude) could be found at greater distances where gravitational lensing searches could also be used (a dark companion to Leo I would be too close even if its dark matter profile is very steeply peaked; see Section 3.1.1).

While we suggest this as a possible target field for a dark galaxy, this interpretation of the unusual velocity of Leo I is far from secure. An alternative possibility is that Leo I is just passing through the Local Group and was never associated with the MW. This possibility might be suggested by the fact that it may have no old stars at all (Lee et al. 1993, Hodge 1994) unlike other dwarf elliptical satellites of the MW such as Ursa Minor (Olszewski & Aaronson 1985).

4.5 Fields of intergalactic planetary nebulae and/or red giants

Intergalactic red giant stars (Ferguson, Tanvir & von Hippel 1998) and planetary nebulae (Theuns & Warren 1997; Freeman et al. 2000) are known to exist in the Virgo and Fornax
galaxy clusters and are thought to have been released from their parent galaxies at some time in the past.

Such objects in the true field are not known but if discovered, the areas around these objects would present reasonable target fields for a dark galaxy search. The ideal would be that these objects might have been accreted by a late-forming dark halo as described in Section 3.5. Certainly if two or more intergalactic stars of any type that are close in physical space can be identified, this would give an excellent target field.

There are a number of theoretical and observational hints that large numbers of low-mass galaxies composed entirely of dark matter exist in the field. The theoretical considerations follow from the prediction of cold dark matter theory that there exist many low-mass galaxies for every massive one. The observational considerations follow from the observed paucity of these low-mass galaxies in the field but not in dense clusters of galaxies; this suggests that the lack of small galaxies in the field is due to the inhibition of star formation in the galaxies as opposed to the fact that their small dark matter halos do not exist. In this work we outline the likely properties of low-mass dark galaxies, and describe observational strategies for finding them, and where in the sky to search. The results are presented as a function of the global properties of dark matter, in particular the presence or absence of a substantial baryonic dark matter component. If the dark matter is purely cold and has a Navarro, Frenk & White density profile, directly detecting dark galaxies will only be feasible with present technology if the galaxy has a maximum velocity dispersion in excess of 70 km s$^{-1}$, in which case the dark galaxies could strongly lens background objects. This is much higher than the maximum velocity dispersions in most dwarf galaxies. If the dark matter in galaxy halos has a baryonic component close to the cosmic ratio, the possibility of directly detecting dark galaxies is much more realistic; the optimal method of detection will depend on the nature of the dark matter. A number of more indirect methods are also discussed.

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