DARK MATTER IN DWARF GALAXIES

John Kormendy
Dominion Astrophysical Observatory
5071 W. Saanich Road
Victoria, B. C. V8X 4M6
Canada

ABSTRACT

This paper reviews the observational evidence for dark matter (DM) in dwarf spiral (dS) and dwarf spheroidal (dE) galaxies. The most secure detection of DM in dwarf galaxies is given by HI rotation curves. They provide estimates of DM halo parameters, i. e., isothermal core radii r_c, central densities ρ_0 and one-dimensional velocity dispersions σ. The smallest DM halo measured so far is in DDO 127 ($M_B = -14.5$ for $H_0 = 75$ km s^{-1} Mpc^{-1}, $r_c \simeq 2.3$ kpc, $\sigma \simeq 27$ km s^{-1}). If this halo is made of neutrinos of mass m_ν, then phase-space constraints imply that $m_\nu > 110$ eV. This is difficult to reconcile with cosmological upper limits giving $\Omega \leq 1$. Ultimately, dE galaxies will provide the strongest constraints on DM in dwarf galaxies; a detailed look at present results shows that they are not yet conclusive.

1. INTRODUCTION

An effective test of any theoretical paradigm is to confront it with observations of extreme objects (Kuhn 1970). It is therefore important to look for dark matter in the smallest galaxies possible. Such observations give leverage to correlations of DM properties with mass. The results have implications for a variety of problems of galaxy formation and evolution. I have time to discuss only a few questions:

(1) Is the ratio of luminous to dark matter a function of galaxy mass? In particular, is there a lower mass limit below which galaxies do not contain DM? If even the smallest visible galaxies have substantial halos, do there exist galaxies which are completely dark?

(2) What are the core radii r_c, central densities ρ_0 and one-dimensional velocity dispersions σ of DM halos? Are the mass distributions isothermal? How do r_c, ρ_0 and σ correlate with galaxy mass and luminosity?

(3) What are the parameters of the smallest DM halos? These provide constraints on the kinds of sub-atomic particles that could make up DM (§4).

(4) Is the visible matter in the smallest dwarfs not self-gravitating? Does this turn off star formation, creating a natural lower limit to the sizes of small galaxies?

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We cannot yet answer these questions. It is only now becoming possible to address them observationally. Some preliminary results are discussed below. This review concentrates on the observations, and stresses the large uncertainties that remain. The smallest galaxies are very difficult to measure and interpret. At present we have estimates of halo parameters only to $M_B \simeq -14.5$, while even the detection of DM in fainter galaxies is uncertain.

Sections 2 and 3 discuss rotation curves of dS galaxies and velocity dispersions of dE galaxies. These appear to be measuring the same kind of object. Observations show that there is a closer kinship between dS and dE galaxies than between dE galaxies and giant ellipticals (see Kormendy 1985 and Aaronson 1986 for reviews). This has led to the suggestion that dEs are dS+Im galaxies that have lost their gas or turned it all into stars. I will therefore compare DM distributions in dS and dE galaxies without regard to optical morphology.

2. HI ROTATION CURVES OF dS + Im GALAXIES

The most clearcut results on DM distributions in small galaxies come from HI rotation curves. The techniques are discussed in this volume by Sancisi and van Albada (1986) and by Freeman (1986). The rotation curve $V(r)$ is measured to the largest possible radius R_{max}. A disk rotation curve is then estimated from the surface brightness distribution assuming that the mass-to-light ratio M/L is constant. This is subtracted in quadrature from $V(r)$, and a halo model (e. g., an isothermal) is fitted to the remainder to get the halo parameters: the maximum or asymptotic rotation velocity V_{max}, $\sigma = V_{max}/\sqrt{2}$, r_c and ρ_0.

Small, late-type galaxies are especially suitable for this procedure. They are relatively easy to interpret: they contain only a (usually exponential) disk and perhaps a halo, but not a bulge. Rotation-curve decomposition is uncertain even in this simple case, and very poorly constrained if there are more than two components. It is also important that dwarf spirals are often rich in HI, even at large radii. Since $V(r)$ for an exponential reaches a maximum at $2.2\alpha^{-1}, \alpha^{-1}$ the scale length, a DM halo can definitely be detected and its r_c measured only if $R_{max}/\alpha^{-1} \gg 1$. *It is worth a great deal of effort to reach the V = constant part of the rotation curve.* Another advantage of dS galaxies is that they are numerous, so that nearby examples with suitable inclination, regularity and large R_{max} can be found. And the assumption that the gas is in circular motion is probably better than the assumption that the velocity distribution is isothermal in dwarf spheroidals.

However, there are also disadvantages and problems. Many are intrinsic to the method. The values of M/L and the assumption that $M/L \neq M/L(r)$ are uncertain. Also, the mass distribution of the disk must be corrected for the contributions of HI and H_2. Internal absorption corrections are poorly known and largest in nearly edge-on galaxies, which are otherwise attractive beause of their small velocity projection corrections. HI warps make the derivation of rotation curves uncertain. And there is always the problem that we do not know *a priori* what to use for the density distribution of the halo. Any error in the assumption that $M/L =$

constant translates directly into an error in the derived halo density distribution. Also, published models are not self-consistent: they ignore the effects of the visible and dark matter on each other. However, this problem is least severe in the smallest galaxies, which contain relatively little visible matter to pull on the dark matter.

Other problems are specific to small galaxies. As L decreases, the corrections for M_{HI} and M_{H_2} grow larger. Also, the rotation velocity approaches zero as L approaches interestingly small values ($M_B \gtrsim -14$). When $V \lesssim \sigma_{HI}$ (the velocity dispersion of the gas), it needs to be corrected for pressure support. Also, the visible galaxy is then not flat, by amounts described by the usual $V_{max}/\sigma_{HI} - \epsilon$ diagram (Illingworth 1977). And the HI distribution and velocity field can be irregular. Finally, as luminosity decreases, the ratio of galaxy size to halo r_c decreases, so it is more and more difficult to reach the V = constant part of the rotation curve. As a result of these problems, rotation curve measurement and decomposition become very difficult at $M_B \gtrsim -15$, and impossible in principle at some $M_B \gtrsim -13$.

There are few galaxies with $M_B \gtrsim -18$ for which adequate rotation curves are available. Several with $-18 \lesssim M_B \lesssim -17$ have been measured by Carignan and Freeman (1985), and by Carignan, Sancisi and van Albada (1985). Ken Freeman (1986) has already discussed this work; parameters of the halos are included in Table 1, below. Published data on several smaller galaxies show that they contain DM halos, but they have not been modelled to derive halo parameters. DDO 154 (Krumm and Burstein 1984) and NGC 6822 (Gottesman and Weliachew 1977) have rotation curves which continue to rise, respectively, to 3.8 and 3.3 times the radius r_{25} of the 25 B mag arcsec^{-2} isophote. Since they are very extended in HI, they would be suitable for modelling. They have $M_B = -16.5$ and -15.6, respectively.

The faintest dwarf spiral measured so far is DDO 127 ($M_B = -14.5$). Surface photometry has been obtained by Souviron, Kormendy and Bosma (1986), and a Westerbork HI velocity field has been measured and modelled by Bosma, Kormendy and Souviron (1986). The galaxy turns out to be exceptionally well suited for halo measurement. It is a regular SABm spiral with a well-defined inclination of 54°. The HI distribution and velocity field are also regular, and are measured out to 1.7 r_{25}. The rotation curve rises almost linearly past r_{25} and then begins to level off. The maximum rotation velocity is $\sim$ 34 km s^{-1}. The disk is exponential, with a scale length of only $\alpha^{-1} = 17'' = 0.4$ kpc. Since $R_{max} = 7.5\alpha^{-1}$, and since $V(r)$ is still rising slightly at R_{max}, it is clear that a substantial DM halo is present. DDO 127 is particularly interesting because *a "maximum disk" model does not fit the rotation curve.* The disk scale length is so short that the disk alone cannot account for most of the rising part of the rotation curve no matter what the M/L. Most of the rotation curve is apparently due to the DM; in particular, the minimum and maximum allowed amounts of disk are not very different. Therefore the halo parameters are relatively well determined despite the usual large uncertainties. Preliminary modelling gives the DM parameters listed in Table 1; these results include corrections for HI mass but not yet for σ_{HI}. (Beam smearing effects are small.) DDO 127 is the smallest galaxy in which DM is securely detected and in which its parameters have been estimated.

Table 1 summarizes DM parameters measured by assuming that halos are isothermal (van Albada *et al.* 1985; Carignan and Freeman 1985; Carignan, Sancisi and van Albada 1985; Bosma, Kormendy and Souviron 1986). For each galaxy I give both minimum- and maximum-halo results. Minimum-halo models use the disk to explain as much of the inner rotation curve as possible; usually they fit out to or slightly beyond the radius where $V(r)$ becomes nearly constant. Maximum-halo models use the halo to fit essentially all of the rotation curve (i. e., $M/L \sim 0$ for the disk). The true halo parameters are bracketed by these results.

Table 1
Parameters of DM Halos in Dwarf Spiral Galaxies

Galaxy	Type	M_B	σ	Min. Halo r_c	Min. Halo ρ_o	Max. Halo r_c	Max. Halo ρ_o
			$\frac{km}{s}$	kpc	$\frac{M_\odot}{pc^3}$	kpc	$\frac{M_\odot}{pc^3}$
NGC 3198	SBc	-19.8	105	12.	0.008	2.8	0.21
NGC 247	SAd	-18.7	90	22.	0.003	5.6	0.043
NGC 300	SAd	-18.1	60	12.	0.0042	3.2	0.060
NGC 3109	SBm	-17.4	40	10.5	0.0024	5.0	0.011
UGC 2259	SBdm	-17.1	57	8.7	0.0073	2.1	0.12
Mean					0.0050		0.089
Dispersion					0.0025		0.078
DDO 127	SABm	-14.5	27	2.3	0.023	1.8	0.044

The correlation of σ with M_B (corrected for internal absorption) is the Tully-Fisher (1977) relation. Otherwise, the sample in Table 1 is too small to show any new regularities. The best-constrained halo parameter is the central density. There is surprisingly little variation in ρ_0 from galaxy to galaxy, despite a range of 100 in L (cf. Bahcall and Casertano 1985). The values of ρ_0 are $\sim$ 18 times larger for the maximum- than the minimum-halo case; the means and dispersions are given in the table. The truth must lie between these cases. Minimum-halo disks are often bar-unstable; not all of the galaxies are barred. Maximum-halo models are implausible because density waves and other self-gravitating structure are then impossible. And, indeed, the better-constrained halo parameters for DDO 127 are intermediate between the minimum- and maximum-disk averages for the other galaxies. The results suggest that there is a fairly canonical central density for DM halos in dwarf spiral galaxies, $\rho_0 = 0.01 - 0.05$ M$_\odot$ pc^{-3}. This value is compared with results for dE galaxies in the next section.

3. THE SEARCH FOR DARK MATTER IN DWARF SPHEROIDAL GALAXIES

For galaxies much fainter than $M_B \simeq -13$, the rotation velocity is less than the velocity dispersion of the gas (e. g., M81 dwA, with $M_B = -11.0$; Sargent, Sancisi and Lo 1983). Then the mass distribution cannot be derived from the rotation curve. A number of other techniques have been tried, including measurements of the velocity differences in binary pairs of dS+Im galaxies (Lake and Schommer 1984), and tidal radii of dE galaxies (Faber and Lin 1983). These have two advantages – they measure almost total masses, and they can easily be applied to large samples of galaxies. But they are plagued by technical problems, so they are not definitive. At present, the best way to look for DM in the smallest galaxies is to measure the dispersion of individual stellar velocities in dwarf spheroidals, and use the virial theorem. This was pioneered in an important series of measurements by Aaronson (1983) and Aaronson and Olszewski (1986).

It is convenient and to some extent plausible to adopt isothermal or King (1966) models for the light and mass distributions. This amounts to a particular choice of the geometric constants omitted in the simplest form of the virial theorem, $M \sim (3\sigma^2)r/G$. In the following, I estimate *central volume densities*; this minimizes the dependence on the assumption of a King model. Central light densities I_0, mass densities ρ_0, and mass-to-light ratios ρ_0/I_0 are given by

$$I_0 = \Sigma_0/pr_c; \tag{1}$$

$$\rho_0 = 166\,\frac{\sigma^2}{r_c^2}; \tag{2}$$

$$\frac{\rho_0}{I_0} = 166\;p\,\frac{\sigma^2}{\Sigma_0 r_c}, \tag{3}$$

where σ is in km s^{-1}, r_c is in pc, the central surface brightness Σ_0 is in L$_\odot$ pc^{-2}, ρ_0 is in M$_\odot$ pc^{-3}, and the geometric factor p is tabulated in Peterson and King (1975) as a function of the usual concentration index log r_t/r_c.

The above procedure suffers from many complications and problems. (1) Like rotation curve decompositions, the models are not self-consistent. (2) King models may not apply to DM halos. The shapes of rotation curves in slightly larger galaxies could partially test this assumption, and King models do fit the central parts of halos, but the small observable radius range gives little leverage, and a good fit does not in any case guarantee that the velocity distribution is isothermal. (3) We think we know r_c for the visible matter, but we do not know it for the DM. This criticism has been emphasized by Madsen and Epstein (1984) and by Cowsik (1985). Certainly the fact that in spiral galaxies r_c^{DM} is larger than the characteristic radius of the visible matter should make us doubt that the two are equal in dwarf spheroidals. If we underestimate r_c, we overestimate ρ_0 and underestimate the total amount of DM. (4) Dwarf spheroidals have remarkably small central densities ρ_0^{vis} of visible matter. Nevertheless, if $\rho_0^{vis} > \rho_0^{DM}$, a central velocity dispersion tells us nothing about DM. We would then need to measure $\sigma(r)$ out to a radius where the visible and DM densities become comparable. This is beyond present capabilities. The visible matter density will in fact turn out to be too high in Fornax and possibly in other dwarf spheroidals.

The most obvious practical problem is the difficulty of measuring sufficiently accurate radial velocities of faint stars (B $\gtrsim$ 18). In the absence of DM, dwarf spheroidals would have $\sigma \lesssim 5$ km s^{-1}. The required precision of ~ 1 km s^{-1} takes ~ 2 h per measurement with present techniques. Reducing systematic errors to comparable levels is more difficult. Carbon stars were the first to be observed (Aaronson 1983; Seitzer and Frogel 1985). They are easy to measure, because they are bright and have strong features. But most turn out to be velocity variables because of atmospheric or binary-star motions (Aaronson and Olszewski 1986). An extensive series of measurements by Aaronson and Olszewski (1986) seeks to determine velocities for ordinary K giant stars, and to eliminate binary stars and other velocity variables using multiple observations. Recent observations by McClure *et al.* (1986) provide an independent check of these results. The Dominion Astrophysical Observatory Radial Velocity Scanner (McClure *et al.* 1985) was used at the Coudé spectrograph of the Canada-France-Hawaii Telescope. Table 2 compares our results with those of Aaronson and Olszewski (1986). Here Δt is the difference in epoch of the two measurements; if it is not listed, Aaronson measured the velocity several times. All velocities are in km s^{-1}. The comparison is reassuring. Three of the stars show agreement as good as we can expect; star 536 may be a velocity variable. Also, it is reassuring that Pryor *et al.* (1986) find velocity dispersions of 2 – 3 km s^{-1} in four metal-poor globular clusters. The stars are like those measured in dEs, both in apparent magnitude and in spectral type. Therefore we *can* measure small dispersions when nature chooses to make them. Apparently the accuracy of the measurements is good.

Table 2
Comparison of Aaronson+ and McClure+ Radial Velocities in Draco

Star	McClure+ V_M	Aaronson+ V_A	$V_M - V_A$	Δt (yr)
249	-292.4 ± 1.0	-295.8 ± 1.0	$+3.4 \pm 1.4$	1.9
267	-291.6 ± 1.4	-290.0 ± 0.9	-1.6 ± 1.7	-
536	-306.0 ± 0.7	-301.9 ± 0.7	-4.1 ± 1.0	-
562	-298.3 ± 1.3	-297.2 ± 1.5	-1.1 ± 2.0	1.0

The available velocity dispersion measurements for five dwarf spheroidal galaxies are given in Table 3. Dispersions are not corrected for measuring uncertainties; the estimated error is only that due to the small number N of stars. The Seitzer and Frogel (1985) measurements of C stars have velocity accuracies of ~ 1.3 km s^{-1}. There is no discrimination against binaries. The Aaronson and Olszewski (1986) stars are ordinary giants except for two C stars in Draco. Repeat measurements have allowed the elimination of 5 of 21 stars observed as binaries.

Table 3
Velocity Dispersions in Dwarf Spheroidal Galaxies

Galaxy	σ (km s^{-1})	N	Reference
Fornax	6.4 ± 2.0	5	Seitzer+ 1985
Sculptor	5.8 ± 2.4	3	Seitzer+ 1985
Carina	5.6 ± 1.6	6	Seitzer+ 1985
UMi	$11. \pm 3.$	7	Aaronson+ 1986
Draco	$9. \pm 2.$	9	Aaronson+ 1986

Table 4 lists structural parameters, central mass densities and mass-to-light ratios derived using equations 1 – 3. Sources of photometry are given in Kormendy (1985). The core radii of the light and dark matter are taken to be equal; this assumption is relaxed later. A self-consistent application of the King models requires several corrections to published data; otherwise M/L is systematically underestimated. Published core radii are corrected from the King (1962) definition in terms of a fitting function to the 1966 definition in terms of the dynamical models. Mean rather than major-axis radii are used; Schechter (1980) shows that the inclination correction factor to M/L then averages to 1 for an ensemble of randomly-oriented galaxies. In principle, the velocity dispersion should be corrected (i) for the mean radius of the stars measured in the galaxy, since $\sigma(r)$ decreases with increasing r in a King model, (ii) for projection, and (iii) for the lowering of the Maxwellian distribution assumed in the model. (The measured dispersion is smaller than the parameter σ in equations (2) and (3) by amounts that are tabulated in King 1966.) For a typical concentration $\log r_t/r_c = 0.6$, the cumulative correction to σ is a factor of 1.8. The corrections to σ ***have not*** been applied in Tables 3 and 4, because it is not clear (see below) that the physical assumptions are valid. If they are applied, ρ_0 and ρ_0/I_0 increase by as much as a factor of 3.

Table 4
Structural Parameters and Mass-To-Light Ratios of Dwarf Spheroidal Galaxies

Galaxy	M_B	$\log \frac{r_t}{r_c}$	μ_0	r_c	Σ_0	I_0	ρ_0	ρ_0/I_0
			Vμ	kpc	$\frac{L_\odot}{pc^2}$	$\frac{L_\odot}{pc^3}$	$\frac{M_\odot}{pc^3}$	
Fornax	-12.3	0.77	23.3	0.50	16.2	0.020	0.028 ± 0.018	1.4 ± 0.9
Sculptor	-10.2	0.76	23.9	0.17	9.7	0.035	0.19 ± 0.16	5.5 ± 4.9
Carina	-8.6	0.50	24.9	0.22	4.0	0.014	0.11 ± 0.07	7.8 ± 6.0
UMi	-7.4	0.75	26.1	0.15	1.2	0.005	0.91 ± 0.51	$175. \pm 131.$
Draco	-7.4	0.52	25.4	0.15	2.5	0.013	0.64 ± 0.34	$48. \pm 35.$

Taken at face value, Table 4 implies the following. There is no evidence for DM in Fornax, Sculptor or Carina (Seitzer and Frogel 1985). However, the central mass-to-light ratios in UMi and Draco are very large, suggesting that substantial amounts of DM are present (Aaronson and Olszewski 1986). But the estimated errors in ρ_0 and ρ_0/I_0 are very large. This is mainly due to the small number of velocity measurements and the large uncertainties in Σ_0. I have followed the usual practice of estimating the error in σ^2 using the variance of its distribution function: $\epsilon(\sigma^2) = \sigma^2\sqrt{2/N}$, $\epsilon(\sigma) = \epsilon(\sigma^2)/2\sigma$. Tremaine (1986) points out that this neglects the asymmetry of the χ^2 distribution of $\Sigma(v_i - \bar{v})^2$. A 68% confidence interval for σ^2 is much wider than $\epsilon(\sigma^2)$ on the high-σ side, but no narrower on the low-σ side. I. e., I have underestimated the sampling errors. Also, the formal errors do not take into account the corrections to σ discussed above, the possible inapplicability of King models, the fact that the models are not self-consistent, and any errors resulting from the assumption that r_c is the same for luminous and dark matter. (If dwarf spheroidals have exponential rather than King-model brightness profiles, then the above corrections to σ are not valid, but the geometric factors are reasonably realistic.) I therefore believe that the results are far from definitive.

An additional worry, or else a reason to wonder whether something very interesting is being discovered, is illustrated in Table 5. This compares central mass densities in dwarf spiral and spheroidal galaxies. Also shown are luminous matter densities in the latter. These are given by I_0 and by $M/L = 2$ as in globular clusters or $M/L = 7$ as in old disks (which assumes the existence of DM like that in the local galactic disk). There are a number of implications. First, there is no contradiction: $\rho_0^{vis} \lesssim \rho_0^{dynamical}$ in all the galaxies. Also, all could have DM halos like those in dwarf spirals (if σ has been overestimated in UMi and Draco). But in Fornax and maybe in Sculptor and Carina, $\rho_0^{DM} \lesssim \rho_0^{vis}$. Then we cannot find DM by measuring *central* velocity dispersions. No one tries to look for DM in galaxies like M31 by measuring the nuclear velocity dispersion. We were so impressed by the low surface brightnesses in dwarf spheroidals that we thought their densities would be "low enough". Evidently this is not the case. Then it is difficult to find DM in Fornax, Sculptor and Carina.

The most important implication of Table 5 involves UMi and Draco. Their dynamical central densities are shockingly high. They are higher than in dwarf spirals, from which we suspect they have evolved. Indeed, these are the highest central DM densities seen in any galaxy so far. In fact, $\rho_0^{dynamical} \sim 10^2\rho_0^{vis}$, so the luminous matter could not be self-gravitating. It is difficult to understand how stars could form without some self-gravity. (Of course, ρ_0^{vis} could have been larger in the past, when – if – dEs were still dSs.) Now, ρ_0^{DM} can be reduced by making $r_c^{DM} \gg r_c^{vis}$. But it is easy to show that as long as the DM remains gravitationally dominant, ρ_0^{DM} can be reduced by no more than a factor of 2 without affecting the visible structure. Then the above discussion remains valid. Only if $\rho_0^{DM} \lesssim \rho_0^{vis}$ (and r_c^{DM} is very large) do these problems disappear. Then we would conclude that DM halos are similar in dE and dS galaxies. If it is appropriate to correct σ upward, these conclusions become much stronger. I therefore suspect that σ has been over-

Table 5
Comparison of ρ_o in dE and dS Galaxies

Galaxy	ρ_o^{vis} $\frac{M_\odot}{pc^3}$		ρ_o $\frac{M_\odot}{pc^3}$	$\rho_o^{dS,min}$ $\frac{M_\odot}{pc^3}$	$\rho_o^{dS,max}$ $\frac{M_\odot}{pc^3}$
	$\frac{M}{L}=2$	$\frac{M}{L}=7$			
Fornax	0.040	0.14	0.028 ± 0.018	↑	↑
Sculptor	0.070	0.24	0.19 ± 0.16	|	|
Carina	0.028	0.10	0.11 ± 0.07	0.005	0.09
UMi	0.010	0.04	0.91 ± 0.51	|	|
Draco	0.026	0.09	0.64 ± 0.34	↓	↓
DDO 127				0.02	0.04

NOTES – Central DM densities for dS galaxies are averages for NGC 247, NGC 300, NGC 3109 and UGC 2259. Minimum- and maximum-halo results are given; the dispersions in ρ_0 are 0.003 and 0.08 $M_\odot$ pc^{-3}, respectively. DDO 127 is listed separately because the minimum- and maximum-halo solutions are similar.

estimated or that $r_c^{DM} \gg r_c^{vis}$ or both. In other words, even the detection of DM in dwarf spheroidal galaxies is presently very insecure.

A plausible guess, which requires testing, is that dwarf spheroidal galaxies contain DM halos like those in dwarf spirals. If so, then $\rho_0^{vis} \simeq \rho_0^{DM}$ in the smallest galaxies. Then self-gravity would only just be important even at the center. Are smaller galaxies prevented from being visible because they cannot make stars? Is the faint end of the luminosity function of galaxies created by the disappearance of "baryonic" self-gravity and star formation? No observation excludes the possibility that there exist many galaxies which are completely dark.

4. CONSTRAINTS ON NEUTRINO DARK MATTER

Tremaine and Gunn (1979) and Gunn (1982) have pointed out that the existence of DM in dwarf galaxies has important implications for the question of whether that DM could consist of massive neutrinos. Currently this seems unlikely, because it would then be difficult to explain galaxy clustering (White 1986). Nevertheless, it is important to examine all constraints on DM composition.

The Tremaine and Gunn argument is as follows. The phase-space density of non-interacting particles can only decrease during violent relaxation from values determined by thermal equilibrium in the early universe. Since neutrinos cannot be packed too closely together, they can make DM halos only if they are sufficiently massive. This provides a lower limit on the neutrino mass m_ν. The Pauli exclusion principle also provides a lower limit, which is less severe by a factor of $2^{1/4}$. Eventually we hope to compare these limits with actual measurements of neutrino masses; at present these are too uncertain (Turner 1986). But we can compare the lower limits with upper limits at which the neutrinos by themselves account for Ω. If $H_0 = 75$ km s^{-1} Mpc^{-1}, the closure density is 5930 eV cm^{-3} (Davis *et al.* 1981). Thermodynamic equilibrium in the early universe implies that the present number density of neutrinos plus antineutrinos is 109 g_ν cm^{-3} (Davis *et al.* 1981), where g_ν = (number of neutrino species)(number of spin states each). Then,

$$\begin{aligned} &\text{if } \Omega_\nu \le 1, && m_\nu \le 55\, g_\nu^{-1}\ \text{eV}; \\ &\text{if } \Omega_\nu \le \Omega_{observed} \simeq 0.2, && m_\nu \le 11\, g_\nu^{-1}\ \text{eV}. \end{aligned} \tag{4}$$

The upper and lower limits are presently on the borderline of being inconsistent.

For an isothermal halo, the Tremaine and Gunn phase-space constraint is:

$$m_\nu^4 > \frac{9\,h^3}{2\,(2\pi)^{5/2}\, g_\nu\, G\, \sigma\, r_c^2}, \tag{5}$$

i.e.,

$$m_\nu > \left(120\ eV\right)\left(\frac{100\ km\ s^{-1}}{\sigma}\right)^{1/4}\left(\frac{1\ kpc}{r_c}\right)^{1/2} g_\nu^{-1/4}, \tag{6}$$

or, since

$$r_c^2 = 9\sigma^2/4\pi G\rho_0, \tag{7}$$

$$m_\nu > \left(106\ eV\right)\left(\frac{100\ km\ s^{-1}}{\sigma}\right)^{3/4}\left(\frac{\rho_0}{1\ M_\odot\ pc^{-3}}\right)^{1/4} g_\nu^{-1/4}. \tag{8}$$

Here h is Planck's constant and G is the gravitational constant. All neutrino species are assumed to have equal masses; otherwise the constraint is more severe. I prefer the form (8) in terms of ρ_0 and σ for several reasons. First, ρ_0 appears to vary relatively little from galaxy to galaxy. It is also better determined from the observations than r_c and σ (see Carignan and Freeman 1985). Then the uncertainties are concentrated in one parameter, σ. Finally, σ is immediately recognizeable from any rotation curve that reaches V = constant = $\sqrt{2}\ \sigma$.

The smallest galaxies for which σ and ρ_0 are sufficiently well determined give:

$$\begin{aligned} &\text{UGC 2259:}\quad m_\nu > 47\, g_\nu^{-1/4}\ \text{eV (min. halo)}; && m_\nu > 95\, g_\nu^{-1/4}\ \text{eV (max. halo)}; \\ &\text{DDO 127:}\quad m_\nu > 110\, g_\nu^{-1/4}\ \text{eV (best fit)}; && m_\nu > 130\, g_\nu^{-1/4}\ \text{eV (max. halo)}. \end{aligned} \tag{9}$$

These values are marginally inconsistent with the upper limits (4). The inconsistency is stronger for larger g_ν or smaller H_0 (the upper limit scales as H_0^2; the lower limit scales as $H_0^{1/2}$). However, since the rotation curves do not unambiguously reach V = constant, σ may have been underestimated. Also, if we relax the assumption of isothermality and construct detailed models of neutrino halos, then the above limits are weakened (Madsen and Epstein 1984). At present, then, neutrino DM is on the borderline of being ruled out by these arguments. Of course, if Aaronson and Olszewski's dispersion measurements in UMi and Draco are taken at face value, they imply a more stringent limit $m_\nu > 560\ g_\nu^{-1/4}$ eV. But this is derived by assuming that $r_c^{DM} = r_c^{vis}$. It is not obvious how r_c^{DM} can be determined so that the σ measurements can be used to constrain m_ν. The best way to improve the ν DM limits appears to be to measure HI rotation curves in smaller dS galaxies.

5. CONCLUSION

The existence and properties of DM in the smallest galaxies have fundamental implications for the DM problem and for our understanding of galaxy evolution. To the extent that measuring techniques are adequate, DM halos have been detected in the smallest galaxies observed. However, we have only recently begun to measure halo parameters and still know little about their systematic behavior. For example, we need to look for relationships between halo parameters analogous to those for elliptical galaxies (Faber and Jackson 1976; Kormendy 1985). This presents us with an obvious opportunity, since HI rotation curves and central velocity dispersions have been measured for only a small fraction of the galaxies that could be observed. It is worth spending considerable effort to push the HI rotation curves to the largest possible radii, and to measure as many accurate radial velocities in dEs as possible. It is also possible that star formation turns off when the "baryonic" matter becomes non-self-gravitating, so that the smallest galaxies are optically invisible. It would therefore be important to extend searches for intergalactic HI clouds (e. g., Lo and Sargent 1979) to more groups and to fainter limits.

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DISCUSSION

TREMAINE: When you are dealing with these small number statistics the distribution of velocities follows a χ^2 distribution. This is quite asymmetric. Then it is not really appropriate to quote a $\pm\sigma$ error. I think that it is relatively easy to get a spuriously low value of M/L and more difficult to get a spuriously high value. Therefore, the errors may not be as bad as you have stated.

LAKE: Your rotation curve for DDO 127 has little curvature. You get constraints on a halo only because the maximum disk is so minimal. If you add the effect of the dispersion of the HI gas, this would raise the central few velocity points and allow you to add much more disk mass. Beam smearing has a similar effect.

KORMENDY: Of course, we will correct for both of these effects in the final analysis. It is true that the amount of disk mass could be somewhat larger than we derive without these corrections. But the disk scale length is so short that the derived halo rotation curve is not very much affected. Also, at large radii, where the rotation curve measures the halo, we observe $V \simeq 35$ km s^{-1}, while the velocity dispersion of the gas is < 10 km s^{-1}. Since the velocities add in quadrature, the dispersion of the gas does not have a large effect.

OSTRIKER: A comment on the apparently high central densities in dwarf spheroidals. If dark halos are made of massive black holes (a perhaps unlikely possibility), then Lacey and I find that a halo in a dwarf spheroidal will contract due to dynamical friction. The distribution of visible stars will expand, drastically reducing the stellar density. Then you expect a high central density of dark matter.

MADSEN: I am somewhat worried about the assumed isothermality of neutrino halos in the discussion of neutrino mass limits derived from dwarf galaxies. The lower mass limits may actually be reduced by a factor of a few if one uses more general assumptions for the neutrino velocity distribution.

KORMENDY: One of the things I did not have time to discuss was the important improvements made by you and others to isothermal assumptions for the halo.

SANDERS: Both you and the previous speaker have shown a decomposition of the rotation curve of UGC 2259 into disk and halo contributions. Is this really fair, since there is no surface photometry for this galaxy?

KORMENDY: You can't make an accurate decomposition without the surface photometry. The best you can do - and this is still more accurate than what I did for the dwarf ellipticals - is to derive an approximate scale length from the size of the object and the central surface brightness estimated by eye from a plate. However, the strongest constraints which I discussed are given by DDO 127, for which there does exist surface photometry.