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H I STUDIES OF THE SCULPTOR GROUP GALAXIES. VII. IMPLICATIONS ON THE DISTRIBUTION AND NATURE OF DARK MATTER IN GROUPS

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ABSTRACT

Results from the large-scale mapping of the H I gas in the Sculptor group are presented. From the kinematical analysis of the members, a mean value of $(M/L_B)_{\rm global} = 9 \pm 5\ M_\odot/L_\odot$ (at the last observed velocity point) is found for the individual galaxies. This is a factor ~ 10 smaller than the $(M/L_B)_{\rm dyn} = 90 \pm 20\ M_\odot/L_\odot$ derived from a dynamical study of the whole group. Mass models, fitted to the rotation curves, suggest a mean density of dark matter (DM) of $\sim 5 \times 10^{-3}\ M_\odot$ pc^{-3} in the halos of the galaxies. This is more than three orders of magnitude greater than the maximum DM density in the intergalactic medium, would all the DM be uniformly distributed in the group. This large density contrast implies that DM is more highly concentrated around the luminous galaxies than uniformly distributed in the group. Under the assumption that the Sculptor group is a virialized system and that all the mass is associated with the galaxies, an upper limit of ~ 40 kpc is derived for the size of the dark halos present in the five late-type spirals of the group. Finally, the implications for the nature of the DM are explored. It is shown that warm nonbaryonic matter is an unlikely candidate. Different baryonic forms for the dark matter are considered and normal low-mass brown dwarfs or massive black holes remain as the most suitable candidates.

Subject headings: dark matter — galaxies: clustering — galaxies: internal motions — radio sources: 21 cm radiation

1. INTRODUCTION

One of the most perplexing discoveries in modern extragalactic astronomy is that observed rotation curves could imply that a large fraction of the masses of galaxies is in the form of dark or unseen matter. Most galaxies studied in detail to date have rotation curves showing that 50%–90% of their mass is not detected by usual means. However, almost nothing is known about the composition or even the exact distribution of dark matter (DM) in the universe. Simple models of the visible material (stars + H I) in individual galaxies are not sufficient to account for the rotation velocities seen at large radii. On the other hand, spherical distributions of DM account fairly well for the large velocities, but no information is gained on the distribution outside the last point of the rotation curves. There, the DM could be as well distributed uniformly in the intergalactic environment or be concentrated around the optical galaxies.

The vast majority of galaxies are distributed in small groups of three to 10 members. Dynamical studies of these groups have shown that the total mass is approximately an order of magnitude larger than the sum of the individual masses of the galaxies. The comparison of the masses and mass-to-light ratios obtained from the kinematics of galaxies and from the virial studies of groups could give us some insight on the DM distribution at large galactocentric radii.

In an attempt to investigate this problem of the DM distribution, an H I and optical study of the Sculptor group was undertaken (Puche & Carignan 1988, hereafter Paper I). Sculptor, being the closest group to the Local Group, and being composed of fairly equally luminous galaxies, is the perfect working ground for a dynamical study. Furthermore, all the major members are late-type galaxies in which there is very little or no bulge, making the modeling of the light distribution that much simpler, and where the H I content is high.

In § 2 a summary of the results obtained for the dynamical study is presented. The H I observations are described in § 3. Section 4 explains the mass models that are used in the analysis of the individual rotation curves. The global parameters, derived from the mass models, are presented in § 5. The implications on the nature of the DM are given in § 6. Finally, the main results of this analysis are summarized in § 7.

2. THE DYNAMICAL STUDY

The first step in this study is to determine the dynamical mass $[(M_T)_{\rm dyn}]$ of the group. For this purpose, the three-dimensional information available on the Sculptor members proves to be very useful. By being able to determine which galaxies are in the front or in the back of the group, it is possible to eliminate interlopers which would otherwise make the mass determination completely erroneous. Paper I of this series has shown that the Sculptor group is composed of five major members (NGC 55, 247, 253, 300, and 7793). Previous membership determinations also included NGC 24 and NGC 45 (de Vaucouleurs 1959), which were rejected in this study as background galaxies.

A virial-type mass estimation of the group yields a value of $(M/L_B)_{\rm dyn} \simeq 90 \pm 20\ M_\odot/L_\odot$ (Paper I). The average value for small groups is between 50 and 150 (Faber & Gallagher 1979).

[1] The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under cooperative agreement with the National Science Foundation.

With the optical parameters given in Table 1, this means a mass of $(M_T)_{\rm dyn} \simeq 2 \times 10^{12}\ M_\odot$.

This result is based on the assumption that the Sculptor group is in virial equilibrium. Estimating the average crossing time of the individual members to be $t_{\rm cr} = 0.7\ H_0^{-1}$ ($H_0 = 100$ km s^{-1} Mpc^{-1}) this assumption might not stand (see Paper 1). Our mass estimate for the group ($M_T = 2 \times 10^{12}\ M_\odot$) is most probably an upper limit. The only way that this would not be the case would be if the galaxies were infalling on radial orbits. A careful look at the three-dimensional distribution and the radial velocities of the Sculptor group galaxies do not imply that they are on inward radial orbits. It should then be kept in mind, in what follows, that our estimate of the virial mass of the Sculptor group is an upper limit to the total mass, if it is physically bound at all.

3. THE H I OBSERVATIONS

All the major galaxies in Sculptor were observed in the line of neutral hydrogen at 21 cm, using the Very Large Array telescope of the NRAO (Carignan & Puche 1990a, hereafter Paper II; Puche, Carignan, & Wainscoat 1990c, hereafter Paper III; Carignan & Puche 1990b, hereafter Paper IV; Puche, Carignan, & van Gorkom 1990b, hereafter Paper V; Puche, Carignan, & Bosma 1990a, hereafter Paper VI). The high spatial resolution obtained with the interferometer allowed the production of detailed maps of the structure of the H I disks. Spectral resolutions of 10 and 20 km s^{-1} were used to determine the velocity fields out to the limit of detectability. For two galaxies, which have more extended structures than the primary beam of the VLA antennas, several fields were mosaicked in order to obtain equal sensitivity across the disk. Figure 1 presents the total H I maps of the five Sculptor group galaxies projected on a spherical coordinate grid of the sky. The galaxies are drawn 4 times larger than they appear on the sky. It can be seen easily that they are well separated from each other and that no present-day interactions are visible.

It was shown for NGC 7793 that past interactions between the members of the group could have affected the structure and kinematics of the galaxies. The low relative encounter velocities ($\sim$100 km s^{-1} assuming isotropic orbits) would have made the interactions more efficient at disturbing the potentials of the individual systems. Since the crossing times are low enough to allow the possibility of past encounters, and the H I distribution of at least one galaxy (NGC 7793) suggests it, this is an argument in favor of the system being bound.

With all the H I data available on the individual members, the next step is to do a proper determination of the rotation velocities as a function of radius, without making any assumptions about the shape of the rotation curve. For this purpose, a full tilted ring model was used, as described in Begeman (1989) and Carignan, Sancisi, & van Albada (1988). The use of a tilted ring model is required since most of the Sculptor group gal-

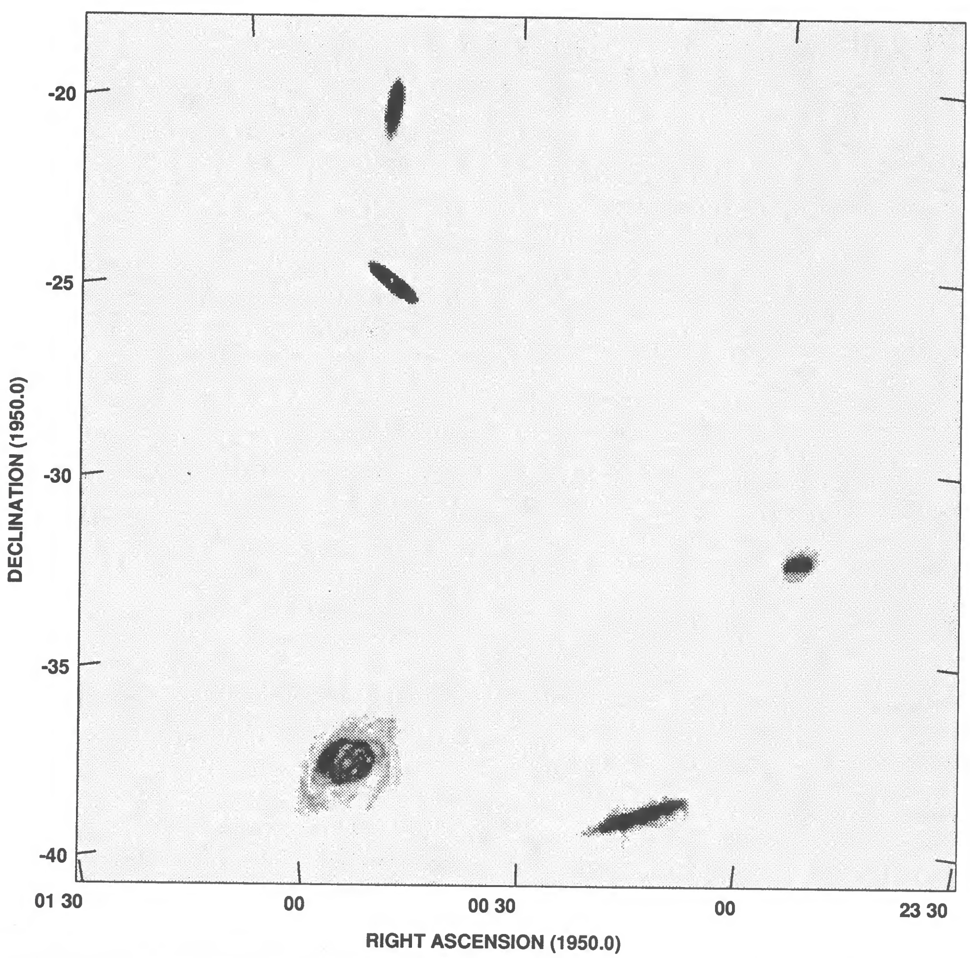
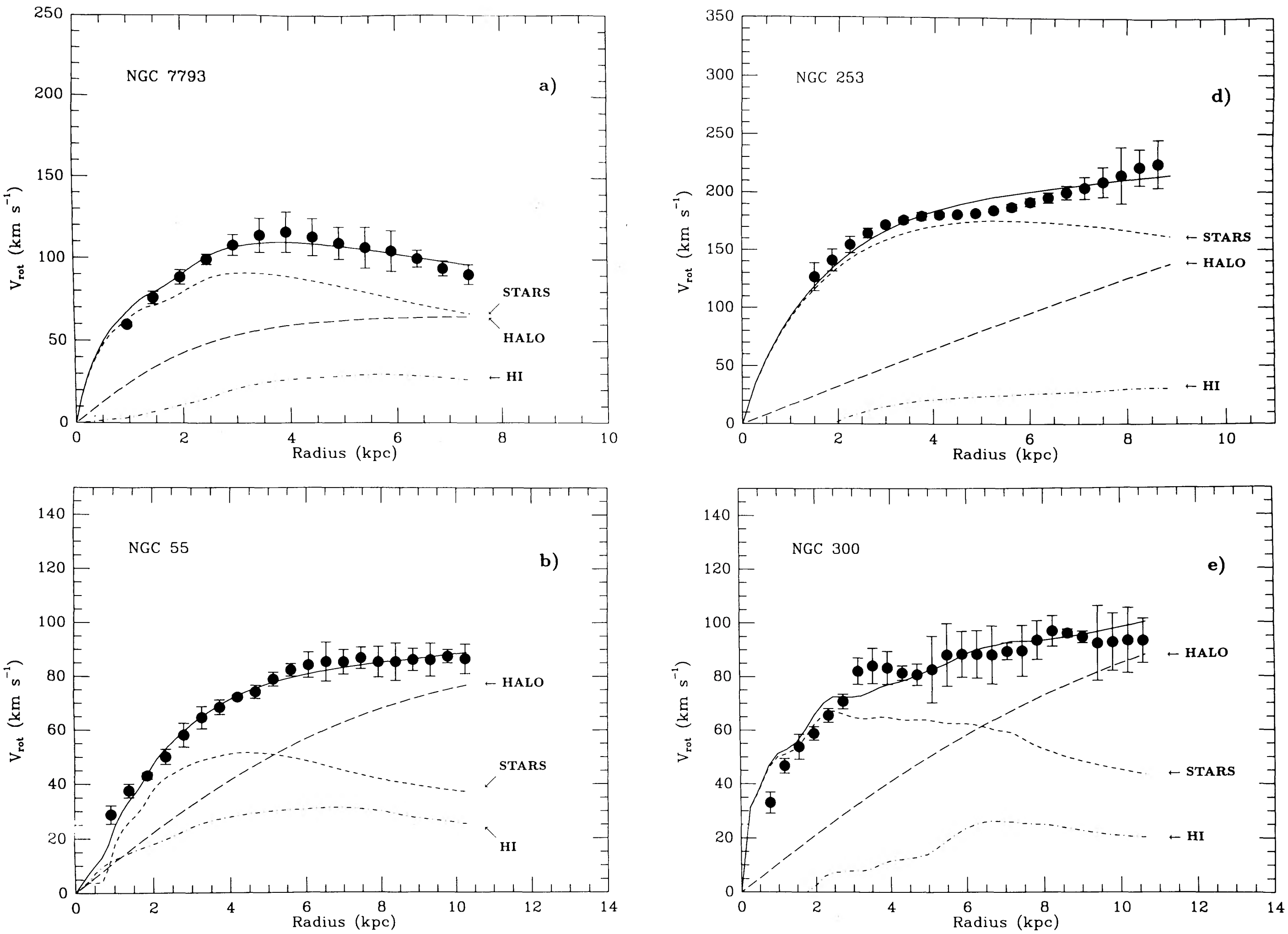


FIG. 1.—Total H I maps of the Sculptor group members on a spherical coordinate grid. The H I distributions are 4 times larger than their actual size on the sky.



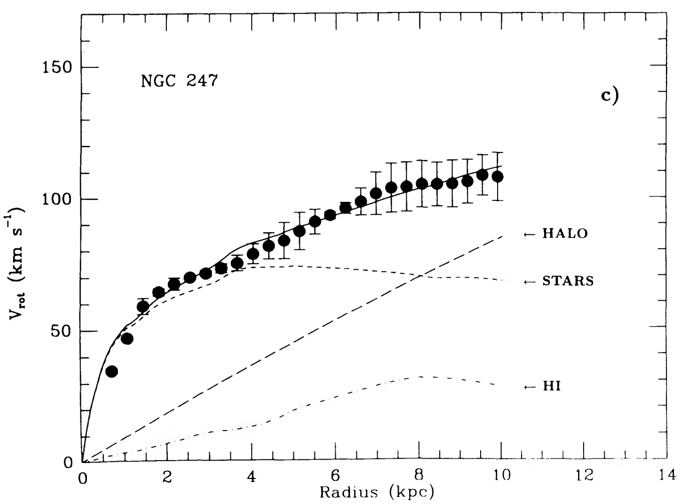


FIG. 2.—Mosaic of the Sculptor group rotation curves and mass models. The dot-dash line is the contribution from the H I disk, the short-dash line is the stellar disk, and the long-dash line is the isothermal halo model.

axies exhibit strong warps in the outer regions. This must be modeled correctly to prevent producing artificially declining rotation curves. For the Sculptor group rotation curves, shown in Figure 2, a steep rise in velocity is observed in the internal regions which flattens out at intermediate distances from the center. For the galaxies NGC 55, 247, 253, and 300, the rotation curve stays flat or continues to rise in the external regions. Only NGC 7793 exhibits a truly declining rotation curve.

4. THE MASS MODELS

In order to determine the mass distribution in each of the galaxies, mass models are fitted to the rotation curves. Those models are described in detail in Carignan (1985) and Carignan & Freeman (1985). Figure 2 shows our three-component models, fitted to the observed rotation curve. The dot-dash line represents the contribution from the H I disk, derived from the VLA maps. The short-dash line is the contribution from the stellar disk derived by elliptically averaging the optical surface photometry data. The photometric parameters of the galaxies are given in Table 1. The long dash line is our isothermal halo model representing the dark matter component. Finally the full line is the final fit to the data obtained by summing quadratically the observed components.

To calculate the mass contribution of the stellar disk, a straight inversion of the *B* luminosity profile (Kalnajs 1983) is performed, where the stellar mass-to-light ratio $[(M/L_B)_*]$, assumed constant throughout the disk, is the only free parameter. For the H I component, the surface densities, determined

TABLE 1

OPTICAL PARAMETERS

NGC	Type	D_{25}[a]	R_{Ho}[b]	α^{-1}[c] (kpc)	B_T^0[d]	Δ[e] (Mpc)	$M_B^{0,i}$[f]	$L_{B_\odot}$[g] ($\times 10^9\ L_\odot$)
55	SB(s)m	37'.8	20'.2	1.61	7.42	1.60	−18.62	4.20
247	SAB(s)d	19.9	12.2	2.90	9.00	2.53	−18.01	2.38
253	SAB(s)c	27.6	17.5	2.39	7.43	2.58	−19.63	10.6
300	SA(s)d	19.6	11.7	2.06	8.38	1.80	−17.89	2.13
7793	SA(s)d	10.1	6.1	1.10	9.33	3.38	−18.31	3.13

[a] Diameter of major axis at $\mu_B = 25.0$ mag arcsec^{-2}.
[b] Radius at $\mu_B = 26.6$ mag arcsec^{-2}.
[c] Optical scale length.
[d] Corrected apparent magnitude.
[e] Distance.
[f] Corrected absolute magnitude.
[g] Corrected absolute total blue luminosity [$M_\odot(B) = +5.43$].

from the moment analysis of the interferometric data, are used. The surface densities are multiplied by 4/3 to account for the He component of the interstellar medium. It is assumed that the H I layer is infinitely thin.

In this analysis the molecular gas component (primarily H_2) is not considered. However, as can be seen in NGC 253, the distribution of CO emission is concentrated in the central regions (Canzian, Mundy, & Scoville 1988), and the density profile follows, on average, the light distribution. Similar distributions are seen in other galaxies (Young & Scoville 1982; Tacconi 1987). Moreover, an attempt has recently been made to show that the CO to H_2 conversion is more or less a constant factor, independent of the emission process throughout the galaxy (Sage, Shore, & Solomon 1990). This implies that the disk component of our model probably contains the molecular gas distribution as well. The scaled value of $(M/L_B)_*$ contains all the mass components distributed approximately as the light in the disk.

The dark halo component is modeled using an isothermal sphere. This distribution has an asymptotic density law in r^{-2}, which translates into a flat rotation curve at large radii. Other potentials having a density distribution $\propto r^{-2}$ have been used and give similar results (van Albada et al. 1985; Kent 1987). Our halo component has two parameters. the core radius r_c and the one-dimensional velocity dispersion σ. The central density is then given by $\rho_0 = 9\sigma^2/4\pi G r_c^2$. The halo parameters, derived for the Sculptor group galaxies, are given in Table 2. Values of densities, masses and mass-to-light ratios at the Holmberg radius are presented in Table 3.

Steeper potentials have been applied to Local Group dwarf spheroidal galaxies (Lake 1990). These r^{-3} and r^{-4} potentials have the advantage of giving a finite mass. However, since our goal has always been to determine the maximum disk models (and hence the minimum DM models) we prefer applying the r^{-2} potential to our data. It will become obvious in § 5 that applying a steeper potential would only reinforce our conclusions about the global distribution of DM in the Sculptor group.

5. THE GLOBAL PARAMETERS OF THE MASS MODELS

One of the goals of the present study is to determine if DM is concentrated around the individual galaxies or if it is more uniformly distributed between them. The most obvious way to do this is to compare the average global mass-to-light ratio $[(M/L_B)_{global}]$ of the galaxies to the $(M/L_B)_{dyn}$ of the group. Table 4 presents the halo density, the ratio of dark to luminous mass, the sum of all the contributions to the mass, and the global mass–to–blue light ratio at the last point of the rotation curves. From this table an average value of $\langle (M/L_B)_{global}\rangle \simeq 9 \pm 5\ M_\odot/L_\odot$ is derived. When the dynamical mass of Paper I and the luminosities from Table 1 are used, then $(M/L_B)_{dyn} \simeq 90 \pm 20\ M_\odot/L_\odot$. These results show that there is an order of magnitude difference between $(M/L_B)_{global}$ of the individual galaxies and the $(M/L_B)_{dyn}$ of the group. One problem with the calculations of M/L_B is that they depend on the estimates of the luminosities of the galaxies. This quantity is difficult to determine for galaxies which have high inclinations and hence higher internal absorption. However, the ratio of $(M/L_B)_{global}$ and $(M/L_B)_{dyn}$ remains the same.

It can be seen in Table 4 that all but one of the galaxies have masses within a factor of 2 of each other, while NGC 253 is 3–5 times more massive. This is expected since the maximum rotational velocity of NGC 253 ($V_{max} \simeq 224$ km s^{-1}) is 2 times higher than for NGC 247 and NGC 300. The total mass of the five galaxies is $1.6 \times 10^{11}\ M_\odot$, with a ratio of dark to luminous mass of $\langle M_{dark}/M_{lum}\rangle \simeq 2.1$ at the last point of the rotation curves.

It is obvious that the rotation curves, derived from the H I velocity fields, do not extend to the limit of the dark halos. Since the rotation curves are flat or continue to rise at the last

TABLE 2

PARAMETERS FROM THE MASS MODELS

NGC	$(M/L_B)^*$ ($M_\odot/L_\odot$)	$M_{(tot)*}$ ($\times 10^9\ M_\odot$)	$M_{(tot)H\,I+He}$ ($\times 10^9\ M_\odot$)	r_c (kpc)	σ (km s^{-1})	ρ_0 ($M_\odot$ pc^{-3})	V_{max} (km s^{-1})
55	0.7	2.7	1.3	8.7	57.0	0.007	87.5
247	4.0	9.5	1.1	24.2	126.9	0.005	111.5
253	8.1	49.0	1.1	26.9	252.8	0.015	213.2
300	2.0	4.3	1.1	12.4	76.8	0.006	102.0
7793	2.2	6.6	8.9	2.5	38.4	0.039	94.1

TABLE 3

DYNAMICAL PARAMETERS[a]

NGC	ρ_{halo} ($M_\odot$ pc^{-3})	M_{dark}/M_{lum}	$M_{(dark+lum)}$ ($\times 10^{10}$ $M_\odot$)	$(M/L_B)_{global}$ ($M_\odot/L_\odot$)
55	0.0021	3.1	1.6	3.8
247	0.0038	1.3	2.1	8.8
253[b]	0.0130	0.8	8.0	15.1
300	0.0045	1.1	1.0	4.7
7793	0.0025	0.8	1.3	4.4

[a] At Holmberg radius (R_{Ho}).

[b] At 0.67 R_{Ho}.

observed point (except for NGC 7793), it would be difficult to believe that the halos do not extend further. It is however possible to estimate the extent of the halos if all the dynamical mass (2.0×10^{12} $M_\odot$) of the group is included in the galaxies. From the mass models, an average radius of 42 kpc for the individual members is needed to account for the total mass. At this radius, the contribution to the mass of the group is 69%, 18%, 7%, 4%, and 1%, respectively, for the galaxies NGC 253, 247, 300, 55, and 7793. It is obvious that more massive galaxies should have more extended halos. For example, NGC 7793 could very well extend only to 10–20 kpc while NGC 253 could have a radius of 50–60 kpc. The value of $\sim$40 kpc indicates however that the average galaxy radius does not need to be as large as 100 kpc or more. If steeper potentials (r^{-3}, r^{-4}), discussed at the end of § 4 are used, the radius of each galaxy becomes even smaller.

It is interesting to compare this result with other work. The halo radius of our own Galaxy was determined from a sample of distant satellite galaxies by Little & Tremaine (1987). By comparing the rotation curve to the orbital velocities of the companions (assumed isotropic) they find an upper limit to the halo radius of about 46 kpc. In an independent fashion the barred galaxy NGC 3992 was studied in detail by Gottesman & Hunter (1982), Gottesman et al. (1984), and Hunter et al. (1988). Even though these authors suggest that no extended halo is needed to explain the mass distribution in this system, a study of the satellites still yields an upper limit of 59 kpc to the extent of the halo. Finally, an H I study by van Moorsel (1982) of a selected sample of pairs of galaxies indicates that halos should extend to one-half of the average separation between the components to explain the dynamical mass derived from the study of the orbital motions of the galaxies. The radius of the halos determined in this way is about 40 kpc.

It is striking that such completely independent and diverse studies yield comparable values for the limiting radius of dark halos in spiral galaxies. All these estimates are based on quite different ways of determining the dynamical mass of the galaxies, and the assumptions about the mass distribution are very different. The biggest common uncertainty, however, comes from the unknown eccentricity of the orbits of the satellites. It would be unlikely, however, that globular clusters, satellite dwarf galaxies, and approximately equal mass galaxies would conspire to orbit around their host system or their companion in systematically highly circular or completely radial orbits.

TABLE 4

DYNAMICAL PARAMETERS[a]

NGC	ρ_{halo} ($M_\odot$ pc^{-3})	M_{dark}/M_{lum}	$M_{(dark+lum)}$ ($\times 10^{10}$ $M_\odot$)	$(M/L_B)_{global}$ ($M_\odot/L_\odot$)
55	0.0018	3.6	1.8	4.3
247	0.0036	1.7	2.6	10.9
253	0.0130	0.8	8.0	15.1
390	0.0027	3.7	2.4	11.0
7793	0.0015	1.0	1.5	4.9

[a] At last point of the rotation curves.

What can be learned from the halo parameters? Even though it was shown that in most cases the halo parameters were not all that well constrained, it is clear that they are intimately related (see Lake & Feinswog 1989). The ratio of the one-dimensional velocity dispersion to the core radius (σ/r_c) remains approximately constant even if both parameters could be varied independently. This means that for any solution of r_c the value of σ appears to adjust itself so as to keep σ/r_c constant, and hence the central density $\rho_0 \propto \sigma^2/r_c^2$ is fairly well constrained. The average ρ_0 for the Sculptor group galaxies is ~ 0.014 $M_\odot$ pc^{-3}. The galaxy NGC 7793, which is less massive, has a very high value of ρ_0 ($\rho_0 \simeq 0.039$). This is consistent with Kormendy's (1987) suggestion that less massive galaxies have more concentrated halos. The optical scale length α^{-1} can also be compared to the halo core radius r_c. The α^{-1}/r_c ratio rises as a function of decreasing mass. Again this indicates that the halos are more concentrated, as compared to the luminous disk, for less massive galaxies (Carignan & Beaulieu 1989).

This result might be worth discussing in a bit more detail. With the wealth of new mass models derived recently, it is possible to draw a better picture of how the disks relate to the density of the halos. Table 5 and Figures 3*a* and 3*b* show the values of the optical scale length in relation with the central density of the dark halos for recently determined mass models. In the linear plot, there is an upper envelope over which the galaxies never go. The correlation is obvious in the log-log plot, except for the galaxy DDO 154. A linear fit to the data is shown. The error bars are typical values for the errors on the parameters fitted to the galaxies. It is to be noticed that even small errors on the distance estimates would have a greater influence on the dispersion of the points than the formal errors of the parameters, since the optical scale length is proportional to the distance D and the central density of the halo is proportional to D^2. More data on dwarf galaxies is urgently needed to corroborate the results. Observations of dwarf irregulars might help in determining the relationship between the DM distribution and the light distribution.

The presence of DM in the Sculptor group galaxies makes no doubt. The central density of the halos is the best constrained parameter describing the DM component. In all cases the maximum disk (hence the minimum halo) is used in the mass modeling. This implies that ρ_0 is most certainly a lower limit to the central density of DM. The mean DM density at the last observed velocity point is approximately three times lower than ρ_0, and gives $(\rho_{dark})_{halo} \simeq 5.0 \times 10^{-3}$ $M_\odot$ pc^{-3}.

Let us suppose now that all the DM present in the Sculptor group, after the last point of the rotation curves, is distributed uniformly across the volume occupied by the group. This implies that 1.84×10^{12} $M_\odot$ is distributed in a volume of 3.5×10^{17} pc^3 (sphere of 20° in diameter at a distance of 2.4 Mpc). The volume density of the dark material would be $(\rho_{dark})_{group} \simeq 5.3 \times 10^{-6}$ $M_\odot$ pc^{-3}. When this value is compared to the average central density of the halos, an overdensity of $\sim$2500 is obtained for the galaxies. This shows that even if the bulk of the mass of the DM component is distrib-

TABLE 5

PARAMETERS OF THE SAMPLE GALAXIES

Name	r_c (kpc)	σ (km s^{-1})	ρ_0 ($M_\odot$ pc^{-3})	$M_B^{0,i}$	$L_{B\odot}$ ($\times 10^9 L_\odot$)	Δ (Mpc)	α^{-1} (kpc)	References
N55	8.7	57.0	0.007	−18.62	2.00	1.60	1.61	1
N247	24.2	126.9	0.005	−18.01	2.38	2.53	2.90	2
N253	26.9	252.8	0.015	−19.63	10.60	2.58	2.39	3
N300	12.4	76.8	0.006	−17.89	2.13	1.80	2.06	4
N2403	8.7	72.0	0.011	−18.95	5.60	3.50	2.20	5
N2841	21.6	158.0	0.009	−19.88	13.30	9.10	2.30	5
N3109	6.0	45.0	0.009	−16.84	1.40	1.70	1.55	6
N3198	10.9	78.0	0.009	−18.62	4.17	3.50	2.20	5
N5033	10.1	101.0	0.005	−18.77	4.80	9.20	4.50	5
N5055	20.9	90.0	0.003	−20.25	18.70	7.70	3.90	7
N6503	4.8	63.0	0.030	−17.36	1.30	3.70	1.10	5
N6946	24.0	82.0	0.002	−21.55	61.90	10.10	4.60	8
N7793	2.5	38.4	0.039	−18.31	3.13	3.38	1.10	9
U2259	5.5	55.0	0.017	−16.45	0.57	7.33	1.34	10
DDO 154	3.0	28.0	0.015	−13.81	0.05	4.00	0.50	11
DDO 170	2.4	73.0	0.017	−15.15	0.23	14.60	1.70	12

REFERENCES.—(1) Paper II; (2) Paper III; (3) Paper IV; (4) Paper V; (5) Begeman 1987; (6) Jobin, & Carignan 1990; (7) Bosma 1981; (8) Carignan et al. 1990; (9) Paper VI; (10) Carignan, Sancisi, & van Albada 1988; (11) Carignan & Beaulieu 1989; and (12) Lake, Schommer, & van Gorkom 1990.

uted uniformly in the group, there is more than three orders of magnitude in density contrast between the intergalactic medium and the central regions of the galaxies. Even if the volume density of the halo material is estimated at the last point of the rotation curves, the density is still $\sim$1000 times greater in the galaxies. This result is independent of the halo models since they give more or less (within a factor of 3) constant densities throughout the volume of the galaxies. This shows clearly that *in the Sculptor group, DM is concentrated in the neighborhood of the luminous galaxies.* If 90% of Little & Tremaine's (1987) mass estimate for the Galaxy is used, the average halo density of the Milky Way is about 10^{-3} $M_\odot$ pc^{-3}. All these values are within a factor of 10 of each other.

6. IMPLICATIONS FOR THE NATURE OF DARK MATTER

In the last 20 years there have been many discussions concerning the nature of DM in the universe (Trimble 1987; Kormendy 1987). Many candidates have been suggested as the principal component of DM. These range from ordinary baryonic neutral or ionized gas particles to nonbaryonic massive particles which interact very weekly with ordinary matter (Turner 1987; Primack & Blumenthal 1984), from Jupiter-sized bodies all the way up to massive black holes. The DM could even be a mix of two or more different particles. From studies of individual galaxies, it is difficult to argue in favor of one candidate or another since the differences that any of these

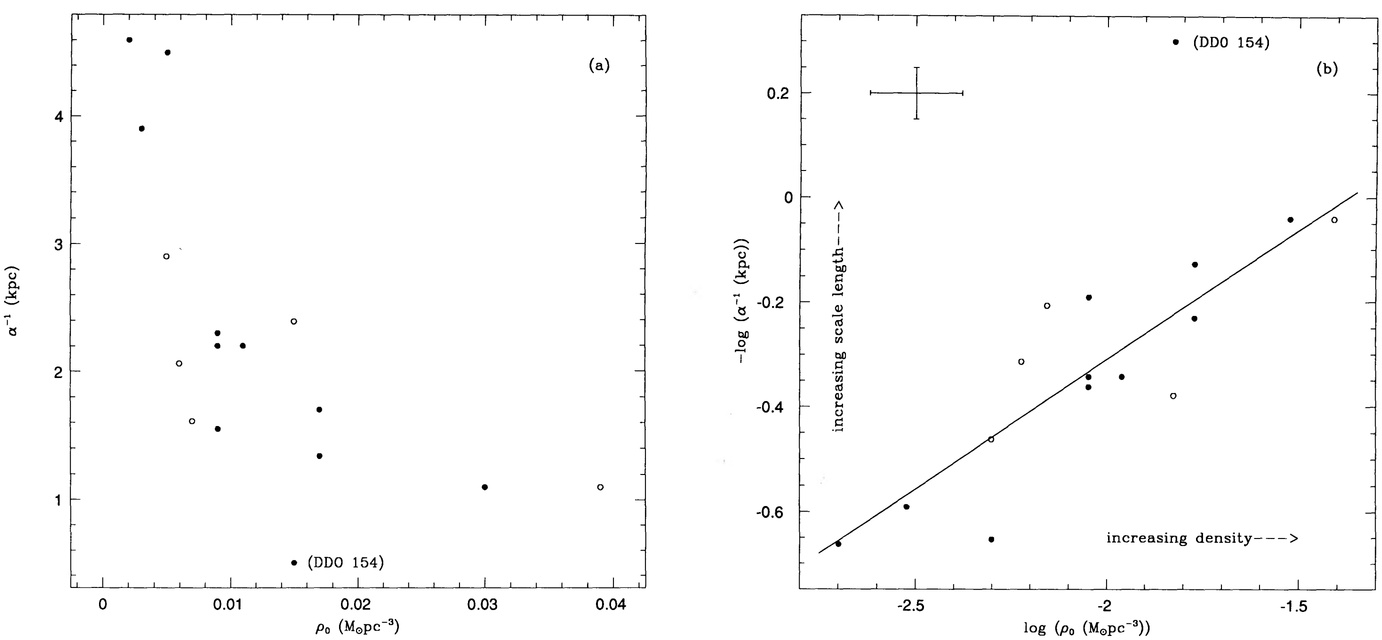


FIG. 3.—(*a*) Linear plot of the values of the optical scale length vs. the central density of the halo. (*b*) Same plot on the log-log scale. The line is a linear fit to the data, made without including DDO 154. Open circles are values for the five Sculptor group members.

could produce on rotation curves is not observable. However, the constraints provided by this study on the mean density of DM and on its distribution around the luminous galaxies justify a reexamination of the question. This is not an attempt to investigate the whole range of possibilities in a systematic way, but only a series of comments on the most popular candidates of dark matter today (see Hegyi & Olive 1986 for a more detailed discussion).

6.1. *The Baryonic Candidates*

From the Sculptor group analysis, we have 5×10^{-3} $M_{\odot}$ pc^{-3} as the density of dark material in the external regions of galaxies, and 5×10^{-6} $M_{\odot}$ pc^{-3} as an upper limit to the density of DM in the intergalactic medium, if DM were uniformly distributed across the group. These values imply column densities of 5×10^{22} atoms cm^{-2} ($l \simeq 20$ kpc) for galaxies and 5×10^{20} atoms cm^{-2} ($l \simeq 800$ kpc) for the intergalactic medium.

The Sculptor group galaxies were observed down to levels of 10^{19}–10^{20} cm^{-2}. No underlying extended structures were observed in the H I distribution. A very deep observation of H I around NGC 3198 shows no gas at column densities less than a few times 10^{19}, while the limiting sensitivity is an order of magnitude less (van Gorkom et al. 1991) in an area covering a square degree. This agrees with very sensitive observations of M33 (Corbelli, Schneider, & Salpeter 1989; Deul & van der Hulst 1987). The H I disks, studied with sufficient sensitivity and resolution, seem to have a sharp cutoff at levels of a few times 10^{19}. It can also be shown that gas would need to be heated to $T_{\rm eq} \simeq 10^6$ K to be in hydrostatic equilibrium in normal halos (Hegyi & Olive 1986). Those two results eliminate intergalactic H I as a probable candidate.

On the scale of the halos of the individual galaxies, many radio continuum studies have yielded upper limits for the amount of hot gas present (Hummel, Dettmar, & Wielebinski 1986; Hummel, Smith, & van der Hulst 1984). A comparison of the H_{α} and continuum radio emission in NGC 55 has shown the two components to be restricted to the plane of the galaxy. Recent surveys of hot gas in the line of H_{α} in NGC 891 (a nearby edge-on system) have shown the presence of diffuse emission away from the plane of the galaxy (Dettmar 1990; Rand, Kulkarni, & Hester 1990). Several "plumes" of emission are observed. However, these are thought to originate from regions of enhanced star formation in the disk and are explained by galactic fountain models. In our own Galaxy, observations of the dispersion measures from globular cluster pulsars at varying latitudes, reveal that the warm and hot gas components are restricted to the plane (Frail & Weisberg 1990). None of the observed emission seems to extend to high enough scale heights or to be dense enough to account for the mass of the halos.

On intergalactic scales, hot gas (at $T_{\rm eq} \simeq 10^6$ K) would produce conspicuous emission. X-ray observations of clusters of galaxies have revealed the presence of an extended very hot medium that could account for as much mass as the optical galaxies (Forman & Jones 1982). However, this hot medium is not seen in loose groups of galaxies, and at the distance of Sculptor would produce readily visible emission.

Let us assume that DM is not dark at all but is made up of unseen normal main-sequence stars in the spherical distribution around the galaxies. The number density of stars in the disk of our Galaxy is $\rho_{\rm stars} \simeq 0.3$ pc^{-3} which corresponds to ~ 30 $M_{\odot}$ pc^{-2} over a thickness of 100 pc (Binney & Tremaine 1987). This value is roughly equal to an average surface density in our galaxy which would be clearly visible on optical images if one was looking at it from a distance of 2–3 Mpc. From the Sculptor group observations the volume density of dark material is $\rho_{\rm dark} \simeq 5 \times 10^{-3}$ $M_{\odot}$ pc^{-3} in the galaxies. This corresponds to ~ 50 $M_{\odot}$ pc^{-2} over a line of sight roughly equivalent to the halo radius at the last points of the rotation curves ($R \simeq 10$ kpc). This value is approximately 4 times smaller than what is estimated for NGC 3198, a much more massive system (Lake & Feinswog 1989). Even with volume densities of order 5×10^{-6} $M_{\odot}$ pc^{-3} the surface density of stars would be ~ 4 $M_{\odot}$ pc^{-2} over a line of sight passing through the group (~ 800 kpc). For solar-type stars, this corresponds to ~ 25.4 mag s^{-2}. Since these values are so high, the halo stars, if they existed, would have been detected on optical images of the Sculptor group galaxies.

6.2. *The Nonbaryonic Candidates*

As was stated in the previous section, the best constrained parameter of the halos is the central density ρ_0. This quantity is related to the phase space density discussed by Lake & Carlberg (1988a, b). The models proposed by these authors imply that at the time of galaxy formation the velocity dispersion of the dark matter was around 20% of the currently observed maximum rotation velocities. From the small difference in the original velocity dispersion, they are able to explain in a very elegant way the origin of the Hubble sequence. Irrespective of the fact that these conclusions might be justifiable or not, the low velocity dispersions implied by the models produce believable final halos. If we take rotation velocities of about 100–150 km s^{-1} for the Sculptor group galaxies, then this implies a velocity dispersion of 20–30 km s^{-1} for the dark halos at the time of turnaround. As we have seen earlier, the present analysis also suggests that the dark matter has a large overdensity around the galaxies compared to the intergalactic medium. This fact, and the low velocity dispersion of the dark halos at the time of galaxy formation, might put very serious constraints on the nonbaryonic candidates for dark matter. Any relativistic particle at the time of decoupling in the early universe must have had time to cool down to a velocity of less than 30 km s^{-1} by $z \simeq 3$. White, Frenk, & Davis (1984) have shown that for a simplified model, the ratio of the present galaxy clustering scale (which is approximately equal to 5 Mpc) to the neutrino free-streaming scale is $\sim 0.4\ \Omega h \Theta^{-2}$. Where Ω is the cosmological density parameter, h is the Hubble constant in units of 100 km s^{-1} Mpc^{-1}, and Θ is the microwave background temperature in units of 2.7 K. This implies free streaming lengths of the order of superclusters or more, hence velocities of several hundred km s^{-1}, much too high to explain the rotation curve models.

It was recently suggested by Lake (1989) that it could be possible to gain some insight into the nature of the dark matter by looking at the phase space density in galaxies as a function of galaxy luminosity. If dark matter is made up of warm particles, the phase space density should be approximately constant as a function of luminosity. On the other hand, if cold dark matter is the dominant component, the phase space density should scale as a function of luminosity. It is suggested that this implies that, in the model of an isothermal sphere, $\sigma \propto L^{1/4}$ and $r_c \propto L^{1/2}$. Then $\rho_0 \propto L^{-1/2}$. Going back to Figure 3 we see that the central density does in fact decrease with optical scale length, and since $L = 2\pi I_0/\alpha^2$ (Freeman

1970) we obtain that the relation log $(\rho_0) \propto -\log(\alpha^{-1})$ shown in Figure 3*b* should be linear. This relation suggests that dark matter is probably cold. Of course, more rotation curves will have to be modeled before any definitive answer could be given on the topic.

6.3. *What is Left?*

All these results leave us with a loose description of what the DM should look like. First, it must be cold, with a velocity dispersion of less than ~ 30 km s^{-1} at the time of galaxy formation. Second, it should not be ionized, neutral, or molecular gas because these would be observable in the Sculptor group. Third, the mass of the individual bodies should be small enough so they would not emit a large quantity of radiation in the visible part of the spectrum.

Several candidates remain plausible as components for the dark matter in galaxies. Of these, the most obvious choices would be the extreme cases of the product of star formation: black holes or brown dwarfs. From the density of the DM required in the galaxies of the Sculptor group, there would be one black hole in the sphere of radius ~ 7 pc around the Sun. However, these massive remnants imply a very different luminosity function in the early stages of the evolution of the Galaxy. Moreover, some of these objects would have accretion disks that would be visible above the soft X-ray background (Hegyi, Kolb, & Olive 1986).

Given that the mass of Jupiter is $\sim 2 \times 10^{30}$ g or 1/1000 $M_\odot$, five Jupiter-sized bodies are required for every pc^3 in order to explain the density of DM. This is very low considering that brown dwarfs could have masses an order of magnitude greater than Jupiter; hence the density could be of only one or less such object pc^{-3}. These masses would be invisible with present means of observation. Since the low-mass end of the luminosity function of the Galaxy is not well sampled, there could be a large quantity of such objects in our system. The problem remains, however, that these brown dwarfs would be difficult to form at an early epoch in the age of the Galaxy where the metal content in the interstellar medium was low and radiative cooling was inefficient.

7. SUMMARY AND CONCLUSIONS

The results from a dynamical and kinematical study of the Sculptor group, from H I observations, have been presented. The main results are as follows:

1. The dynamical analysis of the group yields a $(M/L_B)_{\rm dyn} \simeq 90\ M_\odot/L_\odot$ with a mass $(M_T)_{\rm dyn} \simeq 2 \times 10^{12}\ M_\odot$.
2. From the kinematical analysis of the members, a mean $(M/L_B)_{\rm global} \simeq 9\ M_\odot/L_\odot$ (at the last observed velocity point) is found for the individual galaxies.
3. There is a factor ~ 10 difference between the $\langle (M/L_B)_{\rm global} \rangle$ of the galaxies and the $(M/L_B)_{\rm dyn}$ of the group.
4. The modeling of the rotation curves suggest that a large amount of DM is present in the group. The average density of DM derived at the last point of the rotation curves is $(\rho_{\rm dark})_{\rm gal} \simeq 5 \times 10^{-3}\ M_\odot$ pc^{-3}.
5. Assuming that all the DM outside of the rotation curves is distributed more uniformly in the group, an upper limit of the DM density in the intergalactic medium of $(\rho_{\rm dark})_{\rm group} \simeq 5 \times 10^{-6}\ M_\odot$ pc^{-3} is derived. This value is three orders of magnitude smaller than the DM density around individual galaxies.
6. *The DM is strongly concentrated around the galaxies.*
7. Under the assumption that all the mass is associated with the galaxies, an upper limit of ~ 40 kpc is derived for the size of the dark halos present in the five late-type spirals of the group. This limit corresponds to previously derived halo radii in the Milky Way and in other nearby systems.
8. The DM distribution suggests that warm neutrino-like particles cannot be the major component of the dark material in the group.
9. From the limits imposed by the DM density in the galaxies and in the intergalactic medium, a known gaseous form for the DM is excluded.
10. Several scenarios remain possible: (1) A first generation of stars has left a large number of massive black holes at the onset of galaxy formation, and (2) a population of low mass Jupiter-like objects in a spherical distribution has remained unobserved by optical means. Both these scenarios require a very different star formation process to occur in the protogalactic cloud. (3) Cold dark matter and primordial black holes cannot be eliminated from the candidate list.

The most important aspect of this study is that we might finally become able to put constraints on the distribution of dark matter in the universe. A similar study of other nearby groups is being undertaken and will soon be followed by determinations of galaxy parameters in large clusters. If the conclusions that were reached for Sculptor prove to be universal, then theories of galaxy formation and models for the early universe will have to take into account that the DM is distributed very nonuniformly and that the mass distribution in the universe follows the light distribution.

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