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SOME IMPLICATIONS OF NONLUMINOUS MATTER IN DWARF SPHEROIDAL GALAXIES[1]

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ABSTRACT

Strong constraints are placed on the nature of nonluminous matter if it dominates the gravitational potential of dwarf spheroidal galaxies. In particular, the phase-space constraint in small galaxies sets a lower limit of several hundred eV on particle mass if the dark matter consists of noninteracting fermions. This limit is sufficiently strong to rule out neutrinos. Difficulties of a fundamental nature are also encountered even with more massive noninteracting particles. In scenarios where black holes comprise the nonluminous matter, they have to be less massive than $\sim 100\ M_{\odot}$.

The quasi-exponential light profiles and dark matter in dwarf spheroidal galaxies may indicate a possible evolutionary link to dwarf irregular galaxies. Evidence is presented which supports the view that dwarf spheroidal galaxies are former dwarf irregular galaxies which lost their gas near the Milky Way via ram pressure sweeping.

Subject headings: cosmology — galaxies: formation — galaxies: structure — neutrinos

I. INTRODUCTION

There are seven known dwarf spheroidal (DS) galaxies in the neighborhood of the Milky Way (Hodge 1971; Cannon, Niss, and Nørgaard-Nielsen 1981). Preliminary evidence indicates that these DS satellites may contain appreciable amounts of nonluminous matter and that their luminosity profiles are as well fitted by exponentials as they are by tidally truncated models (Faber and Lin 1983). Although the evidence for these findings is still tentative, we discuss their implications briefly here. Our main purpose is to emphasize the importance of dwarf galaxies to our understanding of galaxy formation and nonluminous matter.

II. ORIGIN OF DWARF SPHEROIDAL GALAXIES

Although dwarf spheroidal galaxies have been classified as members of the elliptical family of galaxies, their nearly exponential profiles resemble those of disk systems. Since their masses are clearly small, a parallel with dwarf irregular (DI) galaxies is appropriate. In this section, we explore the hypothesis that DS galaxies are former DI galaxies that somehow lost their gas. Although DI galaxies appear irregular in blue light, their underlying old stars are smoothly distributed (Hodge 1977, 1978) and their axially averaged luminosity profiles are closely exponential (Hodge 1971). If gas could somehow be removed from a DI galaxy, the young stellar population would soon fade, leaving behind a smooth, low surface brightness galaxy not unlike a DS galaxy. Related views on the origin of DS galaxies have been previously expressed by Einasto *et al.* (1974), Frogel *et al.* (1982), and Aaronson and Mould (1980). To assess this picture for the origin of DS galaxies, we address the following four questions.

1. *Are the structural parameters of DS galaxies consistent with their previously having been DI galaxies*? To examine this question, we have selected three nearby DI galaxies as prototypes. The upper section of Table 1 shows their current properties; the second section shows their hypothetical properties a few billion years after star formation ceases. Fading factors for the stellar population are based on M/L_V versus color from the population models of Larson and Tinsley (1978), plus a final assumed globular cluster M/L_V of 2.5 (Illingworth 1976; Gunn and Griffin 1979).

Comparing the final properties with those of actual DS galaxies in Table 1, we see that two of the DI galaxies (NGC 6822 and IC 1613) are too large to match any DS galaxy, while the third (GR 8) is too small. The extrapolated DI properties nicely bracket the observed DS range, however, and it seems probable that DI galaxies of intermediate brightness would provide a good match.

If only central surface brightnesses are compared, the DI sample can be enlarged to five galaxies (see notes to Table 1). The final central surface brightness after fading based on this sample is 24.4 μ_V, a good match to the observed mean DS value of 23.9 μ_V. Final isophotal radii and internal velocities have also been estimated, as described in Table 1 and the notes, and these quantities again compare favorably. Finally, we note that the ellipticity distribution of the local DS galaxies appears to be consistent, within the errors, with the ellipticity

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TABLE 1

Comparison of Dwarf Irregular and Dwarf Spheroidal Galaxies

Galaxy	Central μ_V (mag arcsec^{-2})	Abs. V mag	Radius at 25.0 μ_V (pc)	Δv (km s^{-1})
Dwarf Irregular Galaxies: Now				
GR 8 (DDO 155) ...	21.6	− 10.6	200	15
IC 1613	22.7	− 15.4	1700	50
NGC 6822...........	20.8	− 16.6	1300	40
Mean of five	22.4	...	...	...
Dwarf Irregular Galaxies: After Fading				
GR 8 (DDO 155) ...	25.8	− 6.3	too faint	15
IC 1613	24.2	− 14.6	~ 1700	50
NGC 6822...........	22.6	− 14.9	$\lesssim$ 1300	40
Mean of five	24.4	...	...	...
Dwarf Spheroidal Galaxies				
Sculptor	23.9*	− 10.9	240	14
Fornax	23.3*	− 13.6	1100	34
Leo I	21.5:	− 11.4	530	21
Leo II................	23.9*	− 9.8	160	12
Draco................	24.6*	− 8.6	30	6.4
Ursa Minor	25.0:	− 8.8	too faint	4.5
Mean of values with asterisk	23.9	...	...	...

Notes.—All photometry has been corrected for Galactic reddening and extinction. Basic data for three DI galaxies are from Hodge (1967, 1977, 1978). Objects in the mean of five are IC 1613, NGC 6822, Ho I, Ho II, and A1008−04. Central surface brightness for the last three was scaled from m_{25} in the RC2 (de Vaucouleurs, de Vaucouleurs, and Corwin 1976) using an additive correction based on IC 1613 and NGC 6822. Sources for internal motions (Δv – HWHM of H I profile) are: GR 8 (Fisher and Tully 1975); IC 1613 (Epstein 1964); NGC 6822 (Rogstad, Rougoor, and Whiteoak 1967). Basic data on DS galaxies are from Hodge (1961*a*, *b*, 1962, 1963, 1964*a*, *b*, 1966, 1971), Hodge and Smith (1974), and Hodge (1983). Central brightnesses for Fornax, Sculptor, and Leo II are photoelectric values; Draco's is inferred from star counts scaled to M3 (see Hodge 1964*b*). The other three are eye estimates from the PSS. Isophotal radii are derived from photoelectric profiles (Fornax and Sculptor) or from star counts normalized to the tabulated central surface brightness (all others). Internal motions are $\Delta v'$ from Table 1 in Faber and Lin (1983).

distributions for DI galaxies as a whole (Thuan and Seitzer 1979).

2. *Do DI galaxies themselves contain enough nonluminous matter to yield DS galaxies with high mass-to-light ratios?* That DI galaxies do appear to contain nonluminous matter has been noted previously by Tully *et al.* (1978) and by Tinsley (1981). To assess the amount quantitatively, we test whether M/L_V will have the right value after stripping and fading. We start with a prototypical DI galaxy, for which $M_{\rm gas}/M_{\rm tot}$ and $(M/L_V)_{\rm tot}$ are both known from 21 cm studies. The value of $M_*/M_{\rm tot}$ before stripping is obtained from a model stellar mass-to-light ratio (taken to be 0.4) based on UBV colors (Larson and Tinsley 1978). $M_{\rm non}/M_{\rm tot}$ is then the fractional remaining mass. The results in Table 2 indicate that nearly two-thirds of the total mass in DI galaxies within the Holmberg radius appears to be in nonluminous form. We further find that M/L_V after fading should be about 28 (Table 2, row [2]), consistent both with the tidal limits in Faber and Lin (1983) and with Aaronson's recent lower limit for Draco of 30 (Aaronson 1983). (The value in Table 2 has been rounded to 30 and used to calculate the internal velocities, $\Delta v'$, in Table 1 of Faber and Lin 1983.)

3. *Is it physically likely that small DI galaxies in the neighborhood of the Milky Way would have had their gas removed by ram pressure stripping?* The rate of mass loss from dwarf galaxies may be estimated quantitatively with a standard formula (Frank and Gisler 1976). For a typical DI galaxy with a mass of $2.4 \times 10^7\ M_\odot$ (Table 1, Faber and Lin 1983) and a gas radius of ~ 1 kpc, an ambient number density of ~ 10^{-6} cm^{-3} is required to

TABLE 2

PREDICTED M/L_V RATIOS OF DWARF SPHEROIDAL GALAXIES

Galaxy	$M_{\rm tot}$ (1)	$M_{\rm gas}$ (2)	M_* (3)	$M_{\rm non}$ (4)	L_V (5)	$(M/L_V)_*$ (6)	$(M/L_V)_{\rm tot}$ (7)
Original dwarf irregular ...	1.00	0.22[a]	0.069[b]	0.71	0.158[c]	0.40[d]	5.8[e]
Final dwarf spheroidal	0.78	0.00	0.069	0.71	0.028[c]	2.5[f]	27.9[g]

[a] Mean of $M_{\rm H\,I}/M_{\rm tot}$ by Fisher and Tully 1975, Thuan and Seitzer 1979, and Tully *et al.* (1978), corrected to $H_0 = 75$ km s^{-1}.

[b] Col. (6) divided by col. (7).

[c] Col. (3) divided by col. (6).

[d] Larson and Tinsley 1978 for $\langle B - V \rangle = 0.40$, $\langle U - B \rangle = -0.20$.

[e] Mean of Tinsley 1981, Faber and Gallagher 1979, and Thuan and Seitzer 1979, corrected to $H_0 = 75$ km s^{-1}.

[f] Typical globular cluster M/L_V of 2.5 assumed (Illingworth 1976; Gunn and Griffin 1979).

[g] Col. (1) divided by col. (5).

strip the gas over a Hubble time. Gas of this density must pervade most of the halo of the Milky Way at a typical distance of roughly 100 kpc.

Such a density is too low to be detected in either our own or other galaxies, even if the gas is quite hot. However, densities of about this order might be expected on indirect arguments. For example, supernovae may provide a nearly hydrostatic galactic corona with a density of $\sim 10^{-4}$ cm^{-3} a few kiloparsecs above the plane (Bregman 1980; de Boer and Savage 1982). For a constant gas temperature of $\sim 10^6$ K (the dynamical temperature of the isothermal halo), one infers a density of $\sim 10^{-6}$ cm^{-3} at 100 kpc. A similar result may be extrapolated from the recent possible detection of an X-ray corona toward the Galactic bulge (Garmire and Nugent 1981). Both of these estimates are uncertain since the density falloff is very sensitive to the actual gas temperature. However, gas densities of the required magnitude do seem plausible, though marginal.

4. *Do the stellar populations of DS galaxies show any signs of relatively recent transition from DI to DS status?* If the condition for gas removal from DS galaxies is indeed marginal, the star-formation histories of DS galaxies would be variable, depending on their orbits, gravitational potentials, and the ambient gas density they encounter. Averaged over all DS galaxies, however, the stellar populations should look considerably younger than those in globular clusters.

Evidence for youthful stars in DS galaxies is well known and includes the presence of carbon stars (see Aaronson, Olszewski, and Hodge 1983, and references therein), anomalous Cepheid variables (Zinn and Searle 1976), and red horizontal branches. Star-formation scenarios based on the bolometric luminosity distribution of carbon stars furthermore indicate widely differing star-forming histories, from galaxies like Carina (Mould *et al.* 1982) and Fornax (Aaronson and Mould 1980), which apparently underwent star formation up until just a few billion years ago, to Sculptor (Frogel *et al.* 1982), Draco (Aaronson, Liebert, and Stocke 1982), and Ursa Minor (Aaronson, Olszewski, and Hodge 1983), which have been dormant a longer period of time. There also seems to be a slight trend for more massive DS galaxies to have more youthful stars (Frogel *et al.* 1982; Aaronson, Liebert, and Stocke 1982). Such a trend would be consistent with gas removal via stripping, since larger galaxies should retain their gas longer on the average and thus have younger stars.

To conclude this discussion of DS galaxies, the evidence as it presently stands on structure, mass-to-light ratios, stellar populations, composition, and halo gas density seems to be moderately consistent with a picture in which DS galaxies were created from DI galaxies via ram pressure sweeping.

III. NEW CONSTRAINTS ON THE NATURE OF NONLUMINOUS MATTER

We next briefly sketch out several constraints that would be placed on nonluminous matter were it to exist in large quantities within dwarf galaxies. One possible constituent of nonluminous matter may be massive neutrinos. Tremaine and Gunn (1978) have derived a limit on the neutrino mass based on the constancy of their phase-space density since cosmological times. Applying their formula (6) with $\sigma = \Delta v/\sqrt{2}$ from Table 1 and r_c from Hodge (1971)[2] yields the following lower limits on m_ν: 150 eV (Fornax), 500 eV (Ursa Minor), 580 eV (Carina), and 600 eV (Draco). These limits are based on an assumed M/L_V of 30. Aaronson's (1983) actual dispersion measurement of 11.3 km s^{-1} for Draco would imply $m_\nu \gtrsim 500$ eV.

These lower limits on m_ν are in strong contradiction to the most conservative limit of 30–100 eV set by the overall mass density of the universe (see Schramm and Steigman 1981). The proven existence of large amounts

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[2] For Carina, $2\bar{r}_1$ from Faber and Lin (1983) was used.

of nonluminous matter in small galaxies would therefore suffice to rule out massive neutrinos as a major constituent of nonluminous matter in the universe. Aaronson (1983) has reached similar conclusions.

Of great importance furthermore is the *precise ratio* of ordinary to nonluminous matter in dwarf galaxies. In the fading picture, DS galaxies start out with the same fractional amount of ordinary matter as DI galaxies, or ~ 30% within the H I radius. Since the nonluminous halo doubtless extends somewhat beyond this point, the ratio of ordinary to nonluminous matter averaged over the *whole* galaxy is probably comparable to that in bigger galaxies and in the universe as a whole, namely ~ 7% (Faber 1982; Gunn 1982).

The above result places strong constraints on galaxy formation models. The standard particle physics model for the early universe sets an upper limit of ~ 1 keV on the mass of any noninteracting particle (Blumenthal Pagels, and Primack 1982). At 1 keV, the Jeans mass is ~ $10^{12}\ M_{\odot}$. Below this mass, only slowly moving, nonrelativistic particles would be bound to density perturbations, and the trapping of nonluminous matter in small galaxies should therefore be drastically reduced. In order to have a Jeans mass comparable to that of the dwarf galaxies, say $\lesssim 10^8\ M_{\odot}$, a particle mass of $\gtrsim 10$ keV is required (see Fig. 1 in Blumenthal *et al.*). However, the existence of such massive noninteracting particles would necessitate fundamental changes to the standard particle physics model (Blumenthal *et al.*).

Alternatively, noninteracting particles may be trapped indirectly by baryonic inhomogeneities in galaxies after the collapse of larger entities, e.g., superclusters (Doroshkevich *et al.* 1981). Current numerical experiments to evaluate the efficiency of trapping by large galaxies within superclusters put it at roughly 10% (J. R. Bond, private communication). Since the efficiency for satellite dwarf galaxies would probably be even smaller, the above scenario may be inadequate to account for the fact that dwarf galaxies seem to be *just as efficient* at trapping nonluminous matter as are more massive objects.

Dwarf galaxies also place important constraints on theories in which nonluminous matter is made up of discrete, massive objects such as black holes. In this case, core collapse would occur on a time scale comparable to the relaxation time (Spitzer and Hart 1971*b*; Lightman and Fall 1978). Inserting values for the mass, velocity dispersion, and density of a typical DS galaxy into a standard formula (Spitzer and Hart 1971*a*), we find that the core collapse time is longer than the Hubble time only if the halo consists mainly of black holes which are more massive than ~ 100 $M_{\odot}$. Since the smooth central luminosity profiles of DS galaxies show no sign of core collapse, black holes or other condensed remnants, if they exist, cannot exceed this mass.

IV. CONCLUSIONS

We conclude with a resumé of badly needed observations on dwarf galaxies. Most important is conclusive evidence one way or the other for the existence of nonluminous matter in these objects. Such evidence would come from the study of 21 cm rotation curves or of stellar velocity dispersion. Next in importance is the dependence of dwarf galaxy properties on mass and environment. In regions where the ambient gas density is high or where galaxies are moving rapidly, gas may be swept from even relatively massive galaxies. DS galaxies in such regions might therefore have high luminosities, high surface brightnesses, and perhaps even show distinct nuclei. The overall DI galaxy population should also be reduced. There actually exists preliminary evidence for such trends among dwarf companions of nearby massive spirals (Einasto *et al.* 1974). Finally, more profile measurements of dwarfs are needed to test whether similar profiles and ellipticity distributions typify both DS and DI classes. Many of these observations are already underway and should provide important new information on dwarf galaxies in the not too distant future.

In conclusion, we point out that our discussion here and in Faber and Lin (1983) is oriented toward the actual existence of nonluminous matter in dwarf galaxies. It should be emphasized, however, that an eventual finding of *little or no* nonluminous matter in dwarf galaxies would have essentially an equal importance to theories of cosmology and galaxy formation.

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