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Dark Matter in Galaxies[1]

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ABSTRACT. Current ideas on the amount, distribution, and nature of dark matter in galaxies are reviewed. Observations indicate that dark halos surround most, if not all, galaxies. Recent evidence suggests that many dwarf galaxies have higher dark-matter fractions than normal galaxies as well as higher central dark-matter densities. Some spiral-galaxy rotation curves are rising and others are falling at the optical radius, thereby weakening the "disk-halo conspiracy." Observational and theoretical techniques to probe the dark halos of ellipticals are becoming more refined, and various methods are being employed to investigate the shape of halos. There are useful constraints on the extent of the dark matter around our own Galaxy, whereas in some other galaxies the edge of the halo may have been detected. Microlensing experiments have recently commenced which may soon uncover the nature of the Galactic dark matter. These and the other issues reviewed here have far-reaching implications for galaxy formation and evolution, and a variety of cosmological questions.

1. INTRODUCTION

One of the outstanding problems in astronomy today is the nature of the dark matter (DM) that pervades the Universe. Over a wide range of scales, the dynamics of astronomical systems are dominated by this material which only reveals its presence through gravitational effects. This is an extremely important issue, since the solution to many astrophysical problems would be more readily obtained if the form of the DM could be established. For instance, attempts to understand galaxy formation would be simplified if we knew whether the DM is primarily baryonic or nonbaryonic and, if nonbaryonic, whether it is "hot" or "cold."

In September 1991, a workshop on *Dark Matter in Galaxies* was held at the Space Telescope Science Institute in Baltimore. The aim of the workshop was to look in detail at one aspect of the DM problem. Specifically, participants concentrated on DM in galaxies, and steered away from DM on larger scales and indirect cosmological considerations that have a bearing on the amount and nature of DM. This encouraged an assessment of current observations that pertain directly to DM in galaxies, so that three fundamental questions could be addressed. How much DM is there in galaxies, how is it distributed, and what is the nature of this DM? Theoretical ideas of direct relevance to these questions were also discussed.

This review is also restricted to the specific topic of DM in galaxies. While much of the material is based on work reported at the workshop, I have also attempted to bring together relevant results from the literature and from recent preprints. Work that was presented at the workshop but which has not appeared elsewhere is referenced by "DMW" (Dark Matter Workshop) throughout. The state of the field was reviewed at length by Trimble (1987), so I have concentrated on significant developments since that time. Other reviewers have discussed specific aspects of DM since that time and these papers are referenced in the relevant sections below. Trimble (1987) and Faber and Gallagher (1979) give a detailed historical perspective of the problem and the broader issues relating to DM. A recent introductory overview of these issues is provided by Tremaine (1992).

I have tried to give values for the dark-to-luminous mass ratio in the various systems of interest, rather than adopting the more conventional approach of quoting a mass-to-light ratio in a given waveband. Part of the motivation is that the gas mass in some galaxies exceeds the stellar mass. In such cases, the quoted luminous mass includes both gas and stars. Many estimates of the amount of DM in galaxies have some dependence on the Hubble constant, H_0. Throughout this review, $h=H_0/100$ km s^{-1} Mpc^{-1} is adopted.

The plan of this article is to start with DM in the vicinity of the solar neighborhood and work upwards and outwards to larger-mass scales and more distant objects. In Sec. 2 the controversial question of DM in the disk of the Milky Way is discussed. The halo of our Galaxy is the

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subject of Sec. 3, whereas Secs. 4 and 5 deal with DM in dwarf spheroidals and dwarf irregulars, respectively. In Sec. 6, observations of DM in spirals are reviewed. New and promising work on the dark halos of ellipticals is covered in Sec. 7. The extent of halos around galaxies in groups and clusters is addressed in Sec. 8, and Sec. 9 is devoted to the shape of dark halos. In Sec. 10, laboratory and astrophysical constraints as well as searches for DM in galaxies are reviewed. Other theoretical consequences of these results, particularly for galaxy formation and the nature of the DM, are discussed in Sec. 11. Conclusions are presented in Sec. 12.

2. THE SOLAR NEIGHBORHOOD

The velocities and distributions of stars perpendicular to the Galactic plane reflect the amount of mass in the local disk of the Milky Way. Velocities can be used to obtain the stellar velocity dispersion perpendicular to the plane $\langle v_z^2 \rangle$, whereas distances provide the density distribution perpendicular to the plane, $\rho(z)$. The gravitational potential due to the disk, $\Phi(z)$, is related to these quantities through the Jeans equation:

$$\rho(z)\frac{d\Phi(z)}{dz}=\frac{-d[\rho(z)\langle v_z^2\rangle]}{dz}, \tag{2.1}$$

so that measurements of $\rho(z)$ and v_z provide an estimate of the density of the disk in the solar neighborhood.

Oort (1932) pioneered attempts to measure the disk density and found that the local disk mass exceeded the value which could be accounted for in visible material (Oort 1960). The problem was later tackled by Bahcall (1984a,b,c) who used star counts of both F dwarfs and K giants, as well as a range of Galactic mass models, to investigate the presence of DM in the solar neighborhood. He numerically solved the combined Poisson and Boltzmann equations, given by

$$\frac{\partial^2\Phi(z)}{\partial z^2}=4\pi G[\rho_{\rm disk}(z)+\rho_{\rm halo}^{\rm eff}] \tag{2.2}$$

and

$$\langle v_z^2\rangle_i\frac{\partial\rho_i(z)}{\partial z}=\frac{-\partial\Phi(z)}{\partial z}\rho_i(z), \tag{2.3}$$

respectively. Here $\rho_{\rm disk}(z)$ is the total disk density, $\rho_{\rm halo}^{\rm eff}$ the density contribution due to the halo, and $\rho_i(z)$ is the density of the ith stellar component with corresponding velocity dispersion $\langle v_z^2\rangle_i$. Bahcall (1984b) assumed that the disk was made up of a finite number of isothermal components to obtain his results. His findings supported the earlier work of Oort and suggested that the density of unseen material in the Milky Way disk was at least 50% that of the observed material. From rotation-curve constraints, the DM was found to be distributed in a disk and to have an exponential scale height less than 0.7 kpc. Thus at the time of Trimble's (1987) review, the evidence pointed towards a significant component of DM in the Milky Way disk. However, more recent developments have altered this view.

Bienaymé et al. (1987) adopted a different approach to estimating the mass density in the Galactic plane. They constructed Galactic models, including the central bulge, visible disk, dark halo, and disk DM, and incorporated a model of the disk stellar populations. The relative contributions of the various terms were constrained by the requirement that the resulting potential should be consistent with observations of the Milky Way rotation curve. Acceptable models had to provide self-consistent solutions to the Boltzmann and Poisson equations. The stellar-density laws were translated into star-count predictions.

In contrast to earlier studies, Bienaymé et al. (1987) found little evidence for disk DM. Their technique suggested a dynamical mass density of 0.09–0.12 $M_\odot$ pc^{-3}, limiting the local-disk DM to a density less than 0.03 $M_\odot$ pc^{-3}, corresponding to a surface density in DM of 24 $M_\odot$ pc^{-2}. Their best-fit model had a DM density of just 0.01 $M_\odot$ pc^{-3}, although no DM was also an acceptable solution. Moreover, Bienaymé et al. (1987) found that a moderate flattening of the dark halo would remove the need for even this small amount of disk DM.

In a subsequent paper, Crézé et al. (1989) addressed the question of why their technique gave different results from those of Oort (1960) and Bahcall (1984b). Their study essentially reversed the Bahcall models to calculate predicted star counts, which were then compared to observed star counts. Crézé et al. (1989) concluded that most Bahcall models, both with and without disk DM, were consistent with the observed star counts, and that the extant data simply did not provide strong constraints on the local-mass density. In other words, Crézé et al. (1989) believed that the errors associated with earlier mass determinations were much larger than previously claimed. Thus there was no conflict between the low- or zero-disk DM densities inferred by Bienaymé et al. (1987) and the much higher DM fractions found by Bahcall.

Around the same time, Kuijken and Gilmore (1989a) introduced a new technique to estimate the surface-mass density of the local disk. Their method also used a tracer population of stars. However, unlike the methods of Bahcall and Oort, it employed the full observed distribution function of velocities and distances of the stellar tracers, rather than assuming that the stellar population could be represented by a finite number of isothermal distributions. This distribution function, along with the spatial-density distribution of the same tracer population, was then used to determine the local surface-mass density.

This method was applied by Kuijken and Gilmore (1989b) to a sample of K dwarfs in the direction of the south galactic pole. They obtained the surface-mass density of visible material by integrating the stellar population near the Sun through the derived gravitational force perpendicular to the disk, and adding to this the interstellar gas. By removing the contribution of the Galactic dark halo, Kuijken and Gilmore (1989b) found a total dynamical surface-mass density of the disk in the solar neighborhood of $46 \pm 9\ M_{\odot}\,\mathrm{pc}^{-2}$. Their value for the surface-mass density in identified material was $48 \pm 8\ M_{\odot}\,\mathrm{pc}^{-2}$, implying that there was no disk DM in the solar neighborhood. Moreover, Kuijken and Gilmore (1989c) analyzed the earlier F- and K-star samples used by Bahcall and, like Crézé et al. (1989), concluded that the available data were either internally inconsistent, or that they provided no reliable evidence for disk DM.

Yet another approach was taken by Knapp (1988; also DMW), who used gas rather than stars to trace the Galactic potential. From an analysis of the relation between velocity dispersion and scale height of molecular hydrogen in the Milky Way, she obtained an estimate of the mid-plane-mass density. The inferred disk mass could be accounted for entirely by known luminous material.

The chief protagonists in this debate then embarked on a discussion in the literature which centered on the correct method of analyzing the data. Gould (1990a) applied a maximum likelihood method to the tracer population of Kuijken and Gilmore (1989b) and found that, even if the same physical assumptions were retained, the disk surface-mass density was higher than claimed by Kuijken and Gilmore, with a value of $54 \pm 8\ M_{\odot}\,\mathrm{pc}^{-2}$. On the basis of this finding, Gould (1990a) claimed that the Kuijken and Gilmore (1989b) study did not severely constrain the amount of disk DM, and that it was consistent with the earlier result of Bahcall. Kuijken and Gilmore (1991) rediscussed their method and argued that their technique was more objective than Gould's still claiming no disk DM within 1.1 kpc of the Galactic plane. In a further study, Kuijken (1991) investigated the presence of DM within 160 pc of the plane, again finding no DM.

The details of this debate are beyond the scope of the present review. In any case, no consensus seems to have been reached on the "correct" method of analysis. As Gould (1989) pointed out, different tracers are sensitive to different hypothetical DM components, which complicates direct comparison between results derived from different data sets.

Part of the apparent discrepancy between these results was probably caused by the systematic uncertainties which dominated the Bahcall calculation of the local-mass density. This problem was noted by Bahcall in his original analysis and studied further by Gould (1990b). The uncertainties include distance-scale errors, nonisothermality of the stellar sample, smoothing of the star counts, spurious stellar-density gradients, and other problems arising from the use of data drawn from different samples. In an attempt to remove some of the confusion, Gould (1990b) devised a technique to assign statistical significance to the local-disk DM density derived using the Bahcall method. He also presented a strategy for obtaining a suitable sample of stars that could be used with the Bahcall method to measure accurately the DM surface density.

Bahcall et al. (1992) have adopted Gould's (1990b) statistical test and observing strategy. They have used a survey of K giants carried out by Flynn and Freeman (1992) that was specifically designed to address this question. This sample is expected to be relatively free from systematic effects. The principal result of Bahcall et al. (1992) is that the hypothesis that there is no disk DM is consistent with the data at a level of 14%. They conclude that the odds are 6 to 1 in favor of the existence of disk DM. Assuming that the DM is distributed in the same way as the visible disk material, the best-fit model has 53% more DM than visible matter.

Despite Bahcall et al.'s (1992) result, the presence of DM in the solar neighborhood seems a less likely proposition than at the time of Trimble's (1987) review. While it can be argued that Bahcall et al.'s (1992) work is the most comprehensive investigation of disk DM, their result is somewhat at odds with other independent studies. It is certainly possible that there is some DM in the Milky Way disk, but there appears to be no clear *need* to invoke such a component. Thus while this issue is not yet closed, the consensus seems to be that the burden of proof has fallen on the advocates of disk DM.

3. THE MILKY WAY HALO

The question of the mass of the Milky Way, which is dominated by the dark halo, was recently reviewed in detail by Fich and Tremaine (1991). I therefore give only a brief description of the techniques that have been used to tackle this question and a summary of recent results. The nature of the DM in the halo of the Galaxy is addressed in Sec. 10.

The globular-cluster system and satellite galaxies of the Milky Way have both been used extensively to estimate the mass and extent of the dark halo. There are two ways that such information may be obtained. The first uses the tidal radii of such objects to probe the Galactic gravitational field. The tidal radius r_t of a satellite object with a perigalactic distance R_p, is related to the mass of the Galaxy through the Roche criterion:

$$\frac{r_t}{R_p} \approx \left(\frac{m}{M(R_p)} \right)^{1/3}, \tag{3.1}$$

where m is the mass of the globular cluster or satellite galaxy and $M(R_p)$ is the Galactic mass interior to R_p. A more precise expression contains factors of order unity that depend on orbital parameters of the objects being used and the assumed density profile of the dark halo.

Innanen et al. (1983) carried out such an analysis using the globular-cluster system of the Milky Way and found that the halo extended to at least 44 kpc with a mass within this radius of $8.9 \pm 2.6 \times 10^{11}\ M_{\odot}$. They further claimed that the density profile of the halo was given by $\rho(R) \propto R^{-1.73 \pm 0.18}$. However, such analyses have certain limitations which Innanen et al. (1983) recognized. For instance, the results are dependent on a knowledge of the mass-to-light ratio of the globular clusters. A bigger problem is obtaining reliable values of the tidal radius. Usually this is obtained by a considerable extrapolation of the observed light profile of the cluster. Consequently, errors are potentially large.

It is perhaps because of these problems that more recent attention has focussed on using the dynamics of such objects to estimate the mass of the Milky Way. This involves measuring the radial velocities and distances of globular clusters and/or satellite galaxies. Since these objects also have non-radial-velocity components, a statistical form of the virial theorem must be used. For N objects with Galactocentric distances r_i and radial velocities v_i, the estimated mass of the Milky Way is

$$M \approx \frac{A}{GN} \sum_{i=1}^{N} v_i^2 r_i, \quad (3.2)$$

where A is a constant of order unity that depends on the orbital distribution of the objects (cf. Binney and Tremaine 1987). Early work, summarized by Trimble (1987) and Fich and Tremaine (1991) consistently led to values around $10^{12}\ M_\odot$ and 100 kpc for the mass and radius of the Galactic halo, respectively. However, Little and Tremaine (1987) developed a sophisticated statistical method to attack the problem which also allowed them to assign uncertainties to the mass determinations (see also Arnold 1992). Their result of a halo mass less than $5\times10^{11}\ M_\odot$ at the 95% confidence level was significantly lower than earlier estimates, and implied a halo radius less than about 46 kpc.

Zaritsky et al. (1989) obtained new velocity data for some of the Milky Way satellites, including a result for Leo I which differed substantially from previous values. Incorporating this into the data set and using the method of Little and Tremaine (1987), they obtained a Milky Way halo mass between $8.1\times10^{11}\ M_\odot$ and $2.1\times10^{12}\ M_\odot$, a good deal higher than Little and Tremaine's (1987) result. There is no mystery here since the difference is attributable to the revised velocity of Leo I. Further support for the higher-mass value was provided by Salucci and Frenk (1989), who considered the effect of the disk on the Milky Way rotation curve and concluded that the halo extended well beyond the 46 kpc derived by Little and Tremaine (1987). Peterson and Latham (1989) obtained a minimum halo mass of $5\times10^{11}\ M_\odot$ assuming that the globular cluster Palomar 15 was bound to the Milky Way, although this result depends somewhat on assumptions about the orbit of the cluster.

Kulessa and Lynden-Bell (1992) have obtained similar results using a maximum-likelihood technique. They find a mass of $1.3\times10^{12}\ M_\odot$ for the Milky Way extending to a radius of 230 kpc. Their favored solution gives a density fall-off for the halo of the form $\rho(R)\propto R^{-2.4}$, where R is the distance from the Galactic center. As in Zaritsky et al.'s (1989) study, the mass estimate of Kulessa and Lynden-Bell (1992) falls considerably if Leo I is excluded from the data set.

The sensitivity of this measurement technique to the inclusion of Leo I is a little worrying. Indeed, Zaritsky et al. (1989) suggest that timing arguments are a more reliable method of calculating the mass of the Milky Way. This technique was first used to estimate the mass of the Local Group of galaxies (Kahn and Woltjer 1959), and is based on the observation that the Milky Way and M31 are approaching one another. This is interpreted as being due to the gravitational attraction of the two galaxies overcoming the Hubble expansion and pulling them together. The current relative velocity is a function of the time that this attraction has been operating and the masses of the two galaxies. The mass of the individual objects is then obtained by assuming a mass ratio for the two galaxies.

Zaritsky et al. (1989) used such a timing argument for the Milky Way and M31, but also carried out a similar calculation for the Milky Way and Leo I. Combining their results, they obtained a Milky Way mass of $(13\pm2)\times10^{11}\ M_\odot$ and a halo radius between about 120 and 210 kpc. The derived radius is dependent on the density profile of the dark halo. The mass is somewhat sensitive to the cosmological model through its dependence on the age of the Universe. Reducing the age of the Universe means that the galaxies have been attracting each other for a shorter time, so more mass must be assigned to them to account for the observed relative velocity. Lake (1992) has emphasized that if the Universe has the critical density required for closure and the cosmological constant is zero, then measurements of the Hubble constant imply an age of the Universe significantly less than that assumed by Zaritsky et al. (1989). This increases the derived mass of the Milky Way.

Other recent work on the mass of the Milky Way includes Merrifield's (1992) study of the rotation curve of the Galaxy from the thickness of the H I layer. This allows the construction of mass models similar to those used in other spiral galaxies (see Sec. 6 below). This technique gives results consistent with other dynamical estimates of the Milky Way rotation curve, but is only applicable out to about 20 kpc and requires an accurate knowledge of R_0 and Θ_0 (the distance of the Sun from the Galactic center and the circular velocity at that radius, respectively) if it is to provide an independent measurement of the quantities of interest.

There now seems to be a consensus that the mass of the Milky Way halo is around $10^{12}\ M_\odot$, with a radial extent of around 100–200 kpc. This corresponds to a dark-to-luminous mass ratio around 10. Attempts to detect DM in the Milky Way halo, as well as theoretical constraints on its nature, are discussed in Sec. 10.

4. DWARF SPHEROIDALS

The faintest known galaxies in the Universe are the dwarf spheroidals. These objects are of particular interest since they appear to be the least luminous stellar systems that contain appreciable amounts of DM. Moreover, as discussed in Sec. 10, they are valuable laboratories for constraining the nature of the DM.

The first hints that dwarf spheroidals were surrounded by dark halos came in the early 1980s. Faber and Lin (1983) used the large tidal radii of local-dwarf spheroidals to infer the presence of DM. [Hodge and Michie (1969) had previously noted that the tidal radius of Ursa Minor was greater than expected, but dark halos were not in vogue at that time and these authors suggested that the dwarf spheroidal might be disintegrating.] From Eq. (3.1) it is apparent that, by assuming a mass model for the Milky Way, the mass of a given dwarf spheroidal can be obtained from its tidal radius. A comparison with the visible mass in stars then indicates whether or not DM is present. However, as noted in Sec. 3, obtaining reliable values for the tidal radii of these galaxies is somewhat problematic.

At about the same time, Aaronson (1983) inferred the presence of significant amounts of DM from the velocity dispersions of stars in Draco. These results were subsequently confirmed by Aaronson and Olszewski (1987), who obtained similar results for Ursa Minor. There are various methods of estimating the dynamical mass from the velocity dispersion, all of which are essentially forms of the virial theorem. The use of velocity dispersions has subsequently proved extremely successful and has become much more practical thanks to recent advances in instrumentation.

4.1 Recent Observational Techniques and Results

The early velocity-dispersion results were based on only a handful of stars and on observations with appreciable measurement errors. More recent programs have concentrated on obtaining velocities for larger numbers of stars in each galaxy and in reducing the errors in the velocity measurements. In fact, two distinct strategies have been adopted. The first is to obtain velocities for a large number of stars using spectrographic observations, typically of the Ca II triplet. Velocity dispersions are obtained to an accuracy of around 5 km s^{-1}, which is comparable to the expected velocity dispersions of these systems. However, the use of fibers allows not only a large number of stars to be obtained with a single exposure, but also makes repeat observations a practical possibility. This is important to reject high apparent velocity dispersions caused by binary stars and pulsating variables. So far, this technique has been applied to Sculptor and Sextans, but all the local-dwarf spheroidals could be studied in this way.

The second strategy is to obtain much higher-resolution velocities. Echelle observations have achieved velocities accurate to 1–2 km s^{-1} in Carina, Ursa Minor, Fornax, and Draco. These observations can go somewhat fainter than the fiber technique, so that potentially more stars are available for observation.

The results of such studies suggest large amounts of DM in most of the nearby dwarf spheroidals, as well as extremely high central DM densities. Mateo et al. (1991) used echelle spectroscopy to obtain velocities for 44 stars and 4 globular clusters around Fornax. Importantly, Mateo et al. (1991) studied two different fields, one near the center of Fornax and another displaced appreciably along the major axis. In both fields, large velocity dispersions were obtained, suggesting the presence of DM with a more extended spatial distribution than the stellar component of the galaxy. Moreover, the central DM density is high with a value of $0.07 \pm 0.03\ M_{\odot}\ pc^{-3}$. This is an order of magnitude higher than typically found in bright spirals (see Sec. 6 below). The repeat observations that Mateo et al. (1991) have for some stars indicate that there are few binaries or pulsating variables contained in the sample.

TABLE 1
Properties of Dwarf Spheroidal Galaxies

Galaxy	M_V	R (kpc)	σ_0 (km s^{-1})	$(M/L_V)_0$	ρ_0 ($M_{\odot}$ pc^{-3})
Fornax	−12.4	145	10.0	5.7	0.073
Sculptor	−11.4	78	7.0	11	0.41
Carina	−9.2	92	8.8	53	0.50
Sextans	−9.1	88	6.8	30	0.07
Draco	−8.9	75	10.5	94	1.3
Ursa Minor	−8.9	69	10.5	83	1.0

Recent results have been obtained for Carina (Mateo et al. 1992a) and Sextans (Suntzeff et al. 1992). Large central mass-to-light ratios are obtained in both cases, implying dark-to-luminous mass ratios around 10. Central DM densities are also high, with values around 0.1 $M_{\odot}\ pc^{-3}$. Since few repeat measurements are available for these galaxies, it is conceivable that binary stars or pulsating variables may be artificially inflating the velocity dispersions. However, if Fornax is typical, this possibility seems unlikely.

Da Costa and Armandroff (1992) have made two or more observations of some of their sample of stars in Sculptor. They have observed stars both inside and beyond the core radius and find high-velocity dispersions in both fields, indicative of an extended dark halo. The central mass-to-light ratio is not extreme, although the central DM density is once again high.

The two faintest local-dwarf spheroidals, Ursa Minor and Draco, appear to have the highest DM fractions. Aaranson and Olszewski (1987, 1988) and Olszewski and Aaronson (1992) report a series of observations of stars in both galaxies, in which a number of repeat measurements have been made. This study has revealed extremely high central M/L_V with values approaching 100 and central densities around 1 $M_{\odot}\ pc^{-3}$ (see, however, Sec. 4.2 below). If the dark halos in Draco and Ursa Minor are more extended than the light, as is typically the case in other galaxies, the total dark-to-luminous mass ratio in these objects is at least 100. Similar observations of Carina and Sextans give central M/L_V values around 50 (Olszewski and Aaronson 1992).

There is some indication from the results summarized above that the dwarf spheroidals closer to the Galactic center have the highest mass-to-light ratio and lowest luminosities. The observations are also consistent with the view that the masses of all the dwarf spheroidals are similar, despite an appreciable range in luminosity. However, observational and modeling uncertainties make these conclusions tentative at this stage.

Further details of the observational techniques and strategies in this field are given in the excellent review by Pryor (1992).

4.2 Constraining the Dark-Matter Distribution

While the above considerations indicate significant amounts of DM and high DM densities in the dwarf spheroidals, there is considerable uncertainty in the quoted values. In most galaxies, these errors are dominated by uncertainties in the structural parameters of the galaxies, rather than measurement errors. The traditional method for obtaining the mass-to-light ratio of dwarf spheroidals is the "core-fitting" technique. This makes the assumption that the mass and light profiles are the same. For dwarf spheroidals this assumption is almost certainly wrong, but the exercise is still instructive. The central density and mass-to-light ratio are given by

$$\rho_0 \approx \frac{9\sigma_0^2}{4\pi G r_c^2} \qquad (4.1)$$

and

$$\left(\frac{M}{L}\right)_0 \approx \frac{9\sigma_0^2}{2\pi G \Sigma_0 r_c}, \qquad (4.2)$$

respectively (Richstone and Tremaine 1986). Here σ_0 is the central projected velocity dispersion and Σ_0 is the central surface brightness. The core radius r_c is defined as the radius at which the surface brightness has fallen to one half the central value. Values for $(M/L)_0$ and ρ_0 [derived from Eqs. (4.1) and (4.2)] for the local-dwarf spheroidals studied to date are given in Table 1. With the exception of the results for Sextans which come from Suntzeff et al. (1992), this table is adapted from Pryor (1992), who based the derived quantities on the observations summarized above.

An alternative to the core-fitting method is to use σ_0 and r_c to obtain a total dynamical mass (Illingworth 1986), under the same assumption that mass traces light. Detailed fitting of the surface-brightness profile is also required (cf. Mateo et al. 1991) and in practice use of the expression in (4.2) is preferred.

It is apparent from Eqs. (4.1) and (4.2) that in order to derive the quantities of interest for a given dwarf spheroidal, an accurate velocity dispersion, core radius, and distance must be obtained. Pryor (1992) summarizes the various measurement errors and shows how they propagate into the final determination of ρ_0 and $(M/L)_0$. In a worst-case scenario, it appears that measurement errors could inflate the derived mass-to-light ratio above its true value, but not sufficiently to remove the need for DM in the dwarf spheroidals identified as having dark halos. However, while the case for DM in the local-dwarf spheroidals is compelling, the values of $(M/L)_0$ and ρ_0 are not well determined. This is not a result of measurement uncertainties, but arises because the mass distribution of the dark halos is unknown. In other types of galaxy, the dark halos are observed to be more extended than the visible component, so it seems reasonable that this is also the case in dwarf spheroidals.

Increasing the core radius of the dark halo and making extreme assumptions about the stellar orbits can reduce the central density by as much as a factor of 20 for Draco and Ursa Minor (Pryor and Kormendy 1990; Lake 1990a). This uncertainty is large, although the Universe would have to be somewhat capricious for the central densities to be so much lower than the estimate given by Eq. (4.1). Even if ρ_0 is lower than the core-fitting value, the total amount of DM in dwarf spheroidals is not reduced so dramatically. This is because in order to reduce ρ_0 one has to assume that the dark halo is much more extended than the visible galaxy. The DM therefore gets pushed to larger radii rather than removed altogether.

There are also limits on the minimum central density ρ_{min} that can be obtained from the data in a model-independent fashion (Merritt 1987; Pryor and Kormendy 1990). The ratio ρ_0/ρ_{min}, where ρ_0 is still given by Eq. (4.1), depends on the concentration (the ratio of tidal radius to core radius) of the galaxy and the quality of the data. In Ursa Minor, for instance, Pryor (1992) finds that $\rho_0/\rho_{min} \approx 8$. While this illustrates that there is still a good deal of uncertainty in the central density, such limits do reduce the possible parameter space. They are also sufficient to show that the dark halos of dwarf spheroidals have significantly higher central densities than those around bright galaxies (see Secs. 5 and 6).

A new technique for obtaining the gravitational potential of spherical systems has recently been explored by Dejonghe and Merritt (1992) and Merritt and Saha (1992). The above discussion illustrates the need for such a technique if we are to get a better idea of the form of DM halos around dwarf galaxies. Merritt and Saha (1992) show that line-of-sight velocities and projected radii provide more powerful probes of the gravitational potential than was previously realized. They further show how to compute likelihood intervals for the gravitational potential based on such a data set. This work is still somewhat preliminary, but may prove to be extremely important.

4.3 Dispensing with Dark Matter

Throughout this section it has been assumed that stellar-velocity dispersions reflect the gravitational potential of a system in virial equilibrium, so that velocities exceeding those that can be explained by the visible mass in dwarf spheroidals are interpreted as evidence for DM. There are two possible ways of avoiding this conclusion that have been discussed in the literature. The first is the suggestion by Milgrom (1983) and others that at low accelerations Newtonian gravity breaks down. Since this suggestion has implications for all types of galaxies, I defer a discussion until Sec. 11.

The second possibility applies specifically to dwarf spheroidals and is based on the idea that the local systems with large-velocity dispersions are not in virial equilibrium. Kuhn and Miller (1989) noted that as dwarf spheroidals orbit the Milky Way the gravitational field that they experience changes. This tidal effect could drive pulsations in the dwarf spheroidals and boost the stellar-velocity dispersion above the equilibrium value. In this case, interpreting velocity dispersions as being due to the gravitational potential of a virialized galaxy would lead to the erroneous conclusion that the galaxy contained DM.

If Kuhn and Miller (1989) are correct, the dwarf spheroidals which show high-velocity dispersions are unbound. This is potentially the most serious problem for the model.

Pryor (1992) suggests that Draco, Ursa Minor, and Carina will have dissolved within 10^8 yr if their velocity dispersions are due to tidal effects. It seems plausible that unbound dwarf spheroidals could remain as identifiable single structures for longer than this. The stars in such a system will certainly drift apart, but they will still tend to follow similar orbits around the Milky Way. Numerical studies may be the only way of resolving this issue.

Some support for the Kuhn and Miller (1989) scenario comes from the observations of the dwarf-spheroidal companions of M31. Caldwell et al. (1992) find that the flattest galaxies have the lowest central surface brightnesses. This is expected in the Kuhn–Miller picture since the galaxies that are experiencing the strongest tidal effects, and thus losing stars the most rapidly, tend to be the most flattened. Another intriguing result that is consistent with the Kuhn–Miller picture is the detection of stars beyond the tidal radius of Sextans (Gould et al. 1992). These ideas are somewhat reminiscent of Lynden-Bell's (1982) suggestion that the dwarf spheroidals around the Milky Way represent tidal debris from disrupted satellite galaxies.

It is not yet clear whether the survival of dwarf spheroidals is a fatal flaw in the Kuhn and Miller (1989) scheme. It is clear, however, that unbound galaxies will lose stars, so a test of the model is to look for stars strung along the orbits of the dwarf spheroidals. The axes of these galaxies are expected to point in the direction of the orbit, thereby providing another observational test.

5. DWARF IRREGULARS

The dwarf-irregular galaxies are particularly useful for DM studies since some of them are extremely gas rich. In such galaxies, the H I rotation curve can be traced to a large number of optical scale lengths. Indeed, recent evidence suggests that in at least one dwarf-irregular galaxy the observed rotation curve is approaching the edge of the dark halo. There is no sharp distinction between bright dwarf irregulars and faint late-type spirals, so the demarcation between the contents of this section and the next is necessarily somewhat arbitrary.

The techniques used to infer the presence and amount of DM in dwarf-irregular and spiral galaxies are also similar. Typically, an H I rotation curve and the virial theorem provide an estimate of the total gravitating mass within the last measured point of the rotation curve. The fraction of this mass provided by the visible stars is found from optical photometry. In dwarf irregulars, however, the gas mass is often substantial and must be included in the inventory. The gas mass is also obtained from the H I observations, along with measurements of H_2 content when available.

One of the most striking results to emerge from recent studies of dwarf irregulars is that at least some of them appear to have much higher DM fractions than normal bright spirals. Related to this is the observation that the dark halo of dwarf irregulars often dominates the dynamics even within the optical radius of the galaxy, whereas in bright spirals the visible disk produces at least half the rotation velocity at small radii. Both trends are similar to

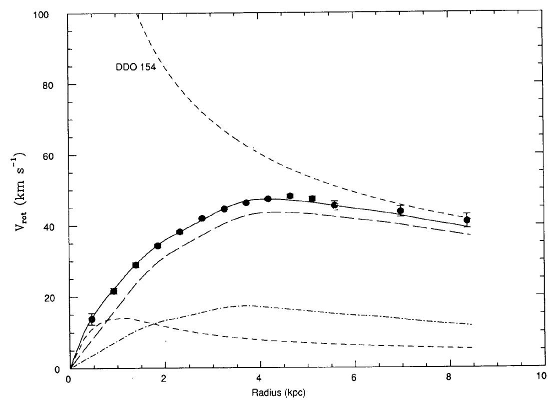

FIG. 1—The rotation curve of DDO 154. The solid line represents the best-fit model. The long dashed curve is the halo contribution for this model, whereas the dot-dashed curve and lower dashed curve represent the velocities due to the H I and stellar disk, respectively. The upper dashed curve is a Keplerian decline for a disk mass of $5\times10^8\ M_\odot$. Figure courtesy of C. Carignan.

those found for the dwarf-spheroidal galaxies described in the previous section. Before discussing these general trends, however, it is instructive to describe some of the observations of individual galaxies.

5.1 Observations of Individual Galaxies

Skillman et al. (1987) studied four dwarf-irregular galaxies in Virgo. By comparing H I rotation curves and optical observations of these galaxies, they found that the mass models of three of these objects required significant DM halos. The central DM density in all three galaxies was around or above 0.01 $M_\odot\ \mathrm{pc}^{-3}$.

DDO 154 is a faint galaxy at $M_B=-13.8$ and is particularly gas rich. Carignan and Freeman (1988) obtained its H I rotation curve out to 7.6 kpc, corresponding to a radius of about $15\alpha^{-1}$, where α^{-1} is the scale length of the stellar component of the galaxy. A more detailed study, including a fuller discussion of the optical properties of this galaxy, was presented by Carignan and Beaulieu (1989). Within the last measured point of this rotation curve the mass ratio of dark-to-luminous material exceeds 10. The central density of the preferred mass model is 0.02 $M_\odot$ pc^{-3}. More recently, Carignan (DMW) has pushed the rotation curve even further to 8.5 kpc. He reports clear evidence that the rotation curve is declining considerably, suggesting that the edge of the dark halo has been reached (see Fig. 1).

GR 8 is a galaxy of even lower luminosity with a B magnitude around -11. H I and optical observations have been carried out by Carignan et al. (1990). The stellar component is relatively normal with the exponential decline characteristic of disk galaxies. However, the rotation axis of the H I disk is parallel to the common major axis of the optical and H I distributions, rather than perpendicular, as is normally the case. The gas dynamics indicate the presence of a dark halo with a core radius that exceeds the optical radius of the galaxy. The density of the halo in this core is estimated to be around 0.07 $M_\odot$ pc^{-3}. It appears that even at such low luminosities, disk galaxies have dark halos.

Lake et al. (1990) obtained H I and optical images of DDO 170. At a magnitude of $M_B=-15.15$ this galaxy is relatively bright for a dwarf irregular. Like DDO 154, the object is gas rich, allowing the rotation curve to be followed to several optical scale lengths. At the last measured point of the rotation curve, the dark-to-luminous mass ratio is around 6. The central DM density is again around 0.01 $M_\odot$ pc^{-3}. DDO 170 has a small companion galaxy. If the two objects are gravitationally bound, then much larger values for the DM fraction in DDO 170 are inferred.

Not all dwarf irregulars show such high DM fractions and central densities. Carignan et al. (1988) found that UGC 2259 had DM properties typical of bright spirals. However, while this galaxy is fairly faint ($M_B \approx -16$), it exhibits a "grand-design" spiral structure. Well-defined spiral arms in a galaxy of such low luminosity are unusual. Moreover, it is possible that grand design spirals can only be produced when the disk mass is a significant fraction of the halo mass (Athanassoula et al. 1987 and Sec. 6.1 below). The lack of a well-defined spiral structure in the majority of low-luminosity disk galaxies may therefore suggest that DM fractions are usually high in these objects.

IC 1613 also appears to have a halo that is less dominant than those around other dwarfs. Lake and Skillman (1989) carried out H I observations of this dwarf irregular, which has a magnitude of $M_B \approx -14.3$, and found a relatively low halo density. However, their H I measurements did not extend far enough to show a turnover in the rotation curve, so the resulting mass models are not strongly constrained.

Studies of late-type spirals also illustrate that there is a good deal of overlap in the properties of their dark halos and those of dwarf irregulars. NGC 7793 with a B magnitude of -18.3 and NGC 5585 at $M_B=-17.5$ are both late-type spirals, considerably more luminous than most of the dwarf irregulars described so far. However, their DM properties are similar to the extreme dwarfs. For NGC 7793, Carignan and Puche (1990a) find for their best-fit model a central density of around 0.04 $M_\odot$ pc^{-3}, considerably higher than normally found in spirals. In the case of NGC 5585, the best-fit central density is even higher at 0.054 $M_\odot$ pc^{-3}, and within the last measured point of the rotation curve the dark-to-luminous mass ratio is around 10 (Côté et al. 1992). While model fitting of this kind has some limitations (see Lake and Feinswog 1989 and Sec. 6.1 below), this illustrates that even some normal spirals have extreme DM properties.

Broeils (1992) has carried out H I and optical observations of the dwarf spiral NGC 1560 ($M_B=-15.9$) and finds a dark-to-luminous mass ratio of around 5 at the last measured point of the rotation curve. Mass models imply a central density ranging from 0.005 to 0.04 $M_\odot$ pc^{-3}, making this object intermediate between typical bright spirals and dwarf-irregular galaxies.

5.2 Trends in Dark-Matter Properties

Broeils (DMW) is involved in an ongoing project to obtain mass models for a large sample of low-luminosity disk galaxies in order to investigate relations between DM properties and galaxy properties. He finds that DDO 168 and DDO 105 have dark-to-luminous mass ratios that are less extreme than some dwarf irregulars and are more characteristic of normal spirals. This raises the interesting question of whether the gas-rich dwarfs like DDO 154 with their high DM fractions are typical, or whether most dwarf irregulars are, like DDO 168 and DDO 105, more similar to bright spirals.

A related issue is the central density of the halo around disk galaxies. Since an observed rotation curve can often be fit by a range of mass models, there is some uncertainty in the derived central density of the dark halo. (It is worth noting that this uncertainty is usually less than that associated with density determinations in dwarf spheroidals.) However, the studies of dwarf irregulars described above indicate that central DM densities are generally higher than those in normal spirals. Typically, the halos of dwarf irregulars have central densities in the range 0.01–0.1 $M_\odot$ pc^{-3}, whereas the halos of bright spirals ordinarily have values between 0.001 and 0.01 $M_\odot$ pc^{-3}.

As is apparent from the above discussion, there is a good deal of scatter in these trends. Thus while faint disk galaxies usually have higher DM fractions and central densities, other parameters may also be important. It is worth noting, however, that the increase in DM fraction with decreasing luminosity in disk galaxies seems to be confined by studies of normal spirals specifically aimed at detecting such relationships. This is discussed further in the next section.

6. SPIRAL GALAXIES

The most convincing evidence for DM in galaxies is provided by the rotation curves of spirals. The rotation velocity of many spirals stays roughly constant out to a large radii rather than declining, as would be expected if the visible stars provided all the gravitating mass. This phenomenon became apparent through optical rotation curves (e.g., Rubin et al. 1980) and, more dramatically, from extended H I rotation curves (Bosma 1978). H I observations have the advantage that the gas disk extends much further than the optical disk, so that it is more difficult to contrive ways to make DM unnecessary. These early results are summarized by Faber and Gallagher (1979).

6.1 Mass Models of Spiral Galaxies

In the 1970s, the idea of dark halos around spirals was not too alarming, since the presence of DM in clusters had been strongly suspected for decades, and there were other reasons for believing spirals might have such halos (e.g., Ostriker and Peebles 1973). A consensus rapidly developed supporting the idea that spirals were surrounded by large amounts of DM. This unusual agreement amongst astronomers was offset by considerable differences of opinion concerning the details of the mass distribution around spirals. The issues are still not resolved and center on the question of how to construct mass models from observational data. It is helpful at this stage to describe some of the debatable aspects of mass decompositions since many of the conclusions summarized later in this section are somewhat dependent on the mass models. Further details are given by Casertano and van Albada (1990) and Rubin (1991).

The traditional method of decomposing spiral galaxy-rotation curves into disk and halo components has been to boost the mass-to-light ratio of the stellar disk to the highest value consistent with the inner rotation curve. The discrepancy at large radii between the velocity produced by such a "maximum disk" and the observed rotation curve is attributed to DM (e.g., van Albada et al. 1985; Kent 1986, 1987a,b, 1988; Sancisi and van Albada 1987).

Apparent support for the reliability of this technique came from observations of the inner regions of spirals where minor features in the rotation curve seemed to correlate with the light distribution. This was interpreted as indicating that the disk was making a significant contribution to the overall rotation in this regime (Kent 1986, 1987b; Casertano and van Albada 1990). Based on more recent observations, Freeman (DMW) also uses this phenomenon to argue in favor of the maximum-disk hypothesis.

However, other considerations point in a different direction. For instance, maximum-disk solutions formally require hollow halos in most galaxies. (The disk is providing all the observed rotation velocity near the galactic center, so the halo has zero mass in its inner regions.) This is clearly unphysical and more realistic models require that the disk in many galaxies has a mass somewhat below the value derived from the maximum-disk hypothesis.

Another difficulty with maximum disks is that some galaxies have similar rotation curves, despite having very different light profiles (van der Kruit 1992). This behavior is difficult to understand in the context of maximum-disk models, since the rotation curve is expected to reflect predominantly the distribution of visible material.

The shape of optical-rotation curves also lies at the center of recent debates. Burstein and Rubin (1985) suggested that such curves could be classified into three distinct mass types based on overall shape. These authors claimed that their mass types did not correlate with the galaxy-light distribution, so that they were reflecting underlying differences in *halo* properties. Persic and Salucci (1991b) also argued that differences in optical-rotation curves reflect changes in halo parameters from one galaxy to another.

Forbes and Whitmore (1989) found that the Burstein–Rubin mass types *did* show a correlation with Hubble type and luminosity, suggesting that the rotation-curve differences could be produced by the gravitational effects of the disk alone. It is therefore not clear whether the Burstein and Rubin (1985) mass types are reflecting the change in the concentration of visible material along the Hubble sequence of spiral galaxies, or whether the differences are produced by the halos. However, the evidence that halos dominate the inner dynamics of dwarf spirals (see Sec. 5 above) suggests that in at least some systems rotation curves predominantly reflect halo properties.

The presence of distinct spiral arms in many disk galaxies has been used to place constraints on the amount of DM in their halos. In particular, it has been argued that the number of spiral arms is related to the mass fraction in the halo. Swing-amplification theory predicts that the dominant mode in a disk surrounded by a dark halo is given by

$$m \approx \frac{M_{\rm disk}+M_{\rm halo}}{M_{\rm disk}} \qquad (6.1)$$

(Toomre 1981), where m represents the number of spiral arms. Since most bright spirals have two dominant arms, this expression is consistent with the finding that the disk and halo have comparable masses within the optical radius of such galaxies (see Sec. 6.2).

Athanassoula et al. (1987) exploited this relation to place constraints on the halos of a sample of spirals. They noted that standard disk-halo mass decompositions typically allowed a large range of disk masses from no disk at all up to the maximum-disk value. Athanassoula et al. (1987) showed that by demanding the $m=2$ mode was dominant, the range of permissible M/L values for the disk could be constrained. Their results further suggested that halos around early-type spirals were more centrally concentrated than those around later types. One caveat to this argument is that hot disks may be able to support spiral structure even in the presence of appreciable DM halos (Bertin et al. 1989).

Flat rotation curves around spirals have usually been interpreted as indicating "isothermal" dark halos. Since $V^2 \propto M/R$ from the virial theorem, constant V implies $M \propto R$ or $\rho \propto R^{-2}$. Many mass models therefore assume that the dark halo can be modeled by a modified isothermal sphere with a density distribution given by

$$\rho = \frac{V_{\rm max}^2}{4\pi G r_c^2 (1+R^2/r_c^2)}, \qquad (6.2)$$

where $V_{\rm max}$ is the asymptotic rotation velocity due to the halo and r_c is the core radius.

Lake and Feinswog (1989) took a critical look at this procedure and reached some dramatic conclusions. Using 37 optical rotation curves and 16 H I rotation curves of spiral galaxies, they examined constraints on the density profiles of the dark halos. If an isothermal halo was assumed, Lake and Feinswog (1989) found that the central density of the halo ($\propto r_c^{-2} V_{\rm max}^2$) was often well determined, but the individual values of r_c and $V_{\rm max}$ generally were not. More significantly, they found that density profiles that tended to R^{-3} or R^{-4} at large radii also gave adequate fits to the data. Similar results were obtained by Bahcall et al. (1982), who also found that density profiles were not well constrained by rotation curves.

While this last result undermines the usual view that dark halos are isothermal, in some ways it is not surprising.

In many mass decompositions the halo core radius is a significant fraction of the galactocentric distance to the edge of the rotation curve. The asymptotic behavior is therefore not well constrained by such data. Even in galaxies where the rotation curve seems to be reaching the edge of the halo, the value of r_c is still a sizable portion of the halo radius. The full consequences of the work of Lake and Feinswog (1989) do not seem to have been absorbed, but it may be that parametric forms of the halo-density distribution are not particularly meaningful.

While a good deal has been learned about the DM around spirals, it is clearly desirable that new mass-modeling techniques be devised to that the remaining uncertainties can be reduced. Casertano (DMW) is investigating methods to maximize the amount of information that can be obtained from H I observations of spiral galaxies. The idea is to model the full H I distribution to extract kinematic information, rather than the usual technique of fitting a tilted-ring model to the two-dimensional velocity field (e.g., Bosma 1978). This work is still in the preliminary stage, but seems to have a good deal of potential.

6.2 The End of a Conspiracy?

Early studies of DM in spirals showed that rotation curves were remarkably flat and featureless. Well outside the optical radius, the halo must provide virtually all of the rotation velocity, whereas in the inner regions maximum-disk solutions indicated that the disk was providing most of the rotation velocity. Even with less massive disks, an appreciable fraction of the inner velocity is attributable to the disk, so the flatness of the rotation curves was puzzling. It appeared that the disk and halo were somehow combining to produce a rotation velocity that stayed constant with radius.

Attempts to decompose the disk and halo (and nuclear bulge if appropriate) confirmed the view that the disk and halo were making comparable contributions to the rotation velocity inside the optical radius. Bahcall and Casertano (1985) summarized results for eight spiral galaxies and found that the ratio of disk mass to halo mass within R_{25} was close to unity for all of the galaxies studied. Carignan and Freeman (1985) obtained a similar result for three galaxies. In view of the flatness of H I rotation curves, this result was not surprising. In order for the disk and halo to both contribute significantly to the overall rotation velocity, while at the same time producing a flat rotation curve, the disk and halo masses within the optical radius are *necessarily* comparable. This apparent fine-tuning between the disk and halo was termed the "disk-halo conspiracy" (e.g., van Albada and Sancisi 1986; Sancisi and van Albada 1987). Such a conspiracy, if genuine, would presumably be telling us something important about galaxy formation and the nature of the DM (e.g., Burstein and Sarazin 1983; Bahcall and Casertano 1985).

Some of the results described in Sec. 5 above indicate cracks in this conspiracy. For instance, in some dwarf irregulars it seems the halo mass is appreciably greater than that of the disk inside the optical radius. Other evidence has come to light which also weakens this conspiracy. Persic and Salucci (1988) devised a method of using the slope of optical-rotation curves to estimate the DM fraction within R_{25}. I return to this and subsequent work below, but note for now that this study suggested an increase in the DM fraction with decreasing spiral-galaxy luminosity. Thus, in the inner regions of *bright* spirals, the disk is the dynamically dominant component, whereas the halo contributes significantly to the rotation curve only at larger radii. In lower-luminosity galaxies, the halo is more likely to dominate at all radii.

This suggests that it is principally in the brightest spirals that one expects some kind of feature in the rotation curve where the transition from disk-dominated to halo-dominated dynamics is reached. This motivated Salucci and Frenk (1989) to investigate the magnitude of such an effect. On the basis of Persic and Salucci's (1988) result, they predicted a drop in the rotation curve of a few tens of km s^{-1} immediately outside the disk of the brightest spirals, whereas in faint, halo-dominated galaxies they predicted the rotation curve remain flat or possibly rise beyond the optical radius. Salucci and Frenk (1989) found some examples of this effect in published H I rotation curves. Sancisi and van Albada (1987) and Baev et al. (1988) also remarked on this phenomenon.

At about the same time, Casertano and van Gorkom (1991) were obtaining H I rotation curves of a number of galaxies. Their approach was to use relatively short-integration times to get crude rotation curves that could be explored further if interesting behavior was uncovered. This allowed a large number of such curves to be obtained. Combining their results with published curves, Casertano and van Gorkom (1991) also identified the drop in the velocities of bright spirals outside the optical radius. Moreover, they found a correlation between the maximum rotational velocity and the slope of the rotation curve beyond the optical radius. (Since spiral-galaxy luminosity and velocity are linked through the Tully–Fisher relation, this is equivalent to a correlation between rotation-curve shape and luminosity.) As predicted by Salucci and Frenk (1989), the rotation velocities of the brightest galaxies fell beyond the optical radius, whereas fainter galaxies showed flat or rising curves. This is illustrated in Fig. 2. It is worth noting that a similar trend was suggested on the basis of optical rotation curves by Rubin et al. (1985). A summary of this earlier work as well as more recent results from optical rotation curves is given by Persic and Salucci (1991b).

Whether these results herald the end of the disk-halo conspiracy depends to a large extend on how one defines the conspiracy. It is clear that not all rotation curves are flat and that their behavior is easily understood in terms of a systematic variation of DM fraction with galaxy luminosity. This variation has a couple of possible of physical explanations (Dekel and Silk 1986; Ashman 1990a), neither of which are conspiratorial. The fact that the mass of DM and visible material within the optical radius is comparable at all can also be understood in terms of simple models of galaxy formation (Fall and Efstathiou 1980).

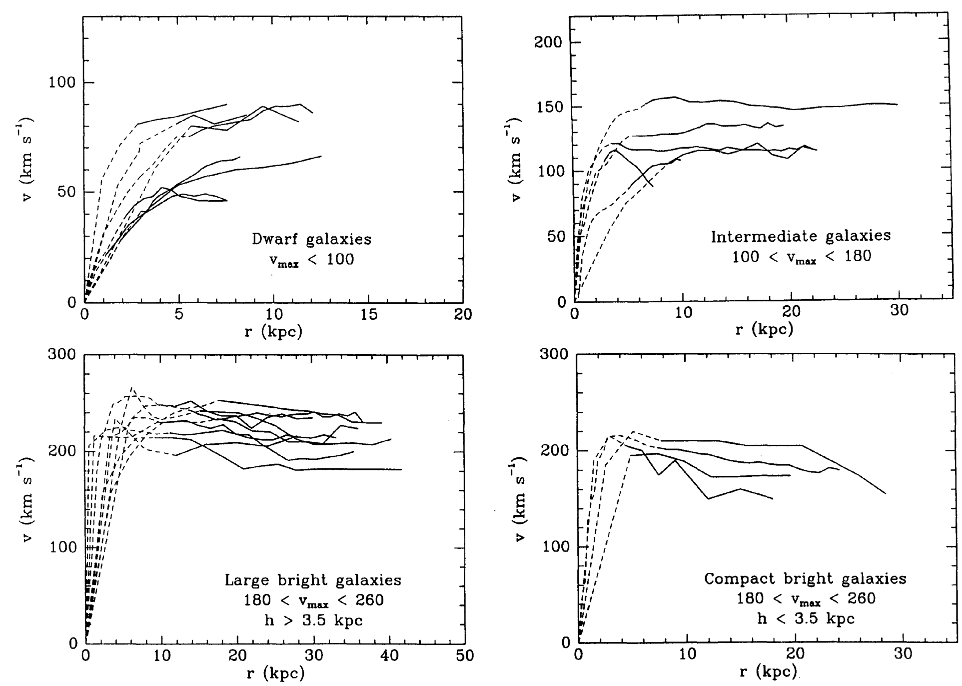

FIG. 2—The families of rotation curves described by Casertano and van Gorkom (1991). Dwarf spirals typically have rising curves, whereas the rotation curves of bright spirals are often falling and exhibit the "disk bump." Figure courtesy of S. Casertano.

Some interplay between dissipating gas and the dark halo may be required to explain the featurelessness of spiral-galaxy rotation curves (Blumenthal et al. 1986; Athanassoula 1988; Ryden 1991), but in my opinion this does not constitute a conspiracy.

6.3 The Dark-Matter Fraction in Spirals

As noted above, Salucci and Frenk (1989) predicted the fall in the rotation curves of bright spirals from Persic and Salucci's (1988) claim that faint galaxies have more DM within R_{25}. Similarly, the empirical results of Casertano and van Gorkom (1991) *could* be the result of an increase in the DM fraction at lower luminosities. However, it is possible to imagine other causes for the correlation between the rotation-curve shape and maximum rotation velocity. Such concerns prompted additional studies of the DM fraction in spirals.

Persic and Salucci's (1988) original approach was based on considerations of centrifugal equilibrium of spiral disks. The presence of the disk pushes the observed rotation velocity above that due to the halo alone. This is somewhat surprising if one recalls that the Tully–Fisher law, which relates velocity to luminosity, and thus disk mass, has a very small dispersion. One might expect variations in DM fraction to cause deviations from the Tully–Fisher law, since they would complicate the relation between velocity and luminosity. Persic and Salucci (1988, 1991a) exploited this fact and showed that accounting for the variation in disk-to-halo mass ratio not only further reduced the dispersion in the Tully–Fisher relation, but also reproduced the observed nonlinearity (Mould et al. 1989).

Persic and Salucci (1990a) applied their method to an enlarged sample of galaxies and found results consistent with their earlier claims. The disk-to-halo mass ratio within R_{25} was found to be proportional to a power law of galaxy luminosity:

$$\frac{M_d(R_{25})}{M_h(R_{25})} \approx A \left(\frac{L_B}{L_B^*}\right)^{\gamma}, \tag{6.3}$$

where $\gamma \approx 0.5$, $A \approx 1$, and L_B^* is the knee of the galaxy-luminosity function. Persic and Salucci (1990b) also used the traditional maximum-disk method to investigate this question. They again found an anticorrelation between DM content within R_{25} and galaxy luminosity.

Yet another independent technique for extracting the DM fraction has been introduced by Salucci et al. (1991). The idea is similar to one pioneered by Tinsley (1981). The starting point is the well-known observation that the surface-brightness profiles of spiral galaxies follow Freeman's (1970) law: $I(R) = I_0 \exp(-\alpha R)$. Here R is galactocentric distance, α^{-1} is the disk scale-length, and the central surface brightness I_0 is roughly constant from one galaxy to another. The mass-to-light ratio of the stellar disk, $(M/L_B)^*$, is obtained from observed galaxy colors and a theoretical relation between color and mass-to-light ratio based on stellar population synthesis models. By converting from surface brightness to surface mass density using $(M/L_B)_*$, Salucci et al. (1991) derived the rotational velocity produced by a disk of a given luminosity. This predicted velocity was compared to observed rotation curves, and excess velocities were attributed to the effects of the dark halo. This technique also indicated an increase in the DM fraction with decreasing luminosity.

One of the advantages of this general method is that it can be applied to large samples of galaxies. Salucci et al. (1992) have extended the technique to galaxies with H I linewidths. Their sample of 258 galaxies is five times larger than any employed in previous investigations of this kind. The trend of higher DM fractions in faint spirals is once again confirmed.

A somewhat different view has been put forward by Jablonka and Arimoto (1992). They carried out an analysis similar to that of Salucci et al. (1991), but using a new population-synthesis model. They found *no* dependence of DM fraction on galaxy color. This may be primarily the result of a poorly selected galaxy sample that is likely to wash out any existing trend. Persic et al. (1992) find that the population-synthesis model of Jablonka and Arimoto (1992), along with a suitably selected galaxy sample, gives results consistent with the usual DM trend.

Other workers have reported results that support higher DM fractions in low-luminosity galaxies. Pierce (1991) found that the total (disk plus halo) *I*-band mass-to-light ratio of disk galaxies increases with decreasing luminosity. Specifically, (M/L_I) rises significantly at a luminosity $\log(L_I/L_\odot) \approx 9.8$, which coincides with the change in the slope of the Tully–Fisher relation. This nonlinearity can be produced by a gradual increase in the mass-to-light ratio with decreasing luminosity (cf. Persic and Salucci 1991a).

Forbes (1992) has used *R*-band photometry and H I rotation curves to estimate the DM fraction in a sample of spirals. He finds clear evidence for larger amounts of DM in the fainter galaxies.

One novel approach has been adopted by Maloney (1992), who uses low-redshift Lyman-α absorption features to infer the properties of dark galactic halos. These features are assumed to be produced by gas within spiral halos. He concludes that either typical dark halos extend to very large radii (around 1 Mpc; a possibility that is shown to be unlikely in Sec. 8), or that the DM fraction in low-luminosity galaxies is higher.

Kormendy (1990) used published mass models of disk galaxies derived from rotation curves to study trends in the DM content. He too found a tendency for lower-luminosity disk galaxies to have higher DM fractions and central densities. Two relations of interest are

$$\rho_0 \approx 0.0071 \left(\frac{L_B}{10^9 L_{B\odot}}\right)^{-0.15} M_\odot\ \mathrm{pc}^{-3} \qquad (6.4)$$

and

$$r_c \approx 5.9 \left(\frac{L_B}{10^9 L_{B\odot}}\right)^{0.34} \mathrm{kpc}, \qquad (6.5)$$

where r_c is the core radius of the DM halo. As Kormendy (1990) stressed, these relations contain a good deal of uncertainty, although they do fit in with the general trend that has emerged over the last few years. Borgani et al. (1991), using the mass-decomposition method of Persic and Salucci (1990a), found that the *mean* density within the optical radius is given by $\langle\rho\rangle \approx 0.003\ (L_B/L_B^*)^{-0.9}\ M_\odot\ \mathrm{pc}^{-3}$.

It is worth noting that Eq. (6.1) is consistent with an increase in DM fraction with decreasing galaxy luminosity. If $M_{\mathrm{halo}} \gg M_{\mathrm{disk}}$, then m becomes large, and organized spiral structure is unable to form. Low-luminosity disk galaxies rarely have well-defined spiral arms, consistent with the view that their halos dominate the dynamics even within the optical radius.

Phookun (DMW; also Phookun et al. 1992) is using this idea to study one-armed spiral galaxies. From Eq. (6.1) it is apparent that disks with no surrounding halo are dominated by the $m=1$ mode and are therefore likely to exhibit a single spiral arm. NGC 4027 is one such example under study. Unfortunately, it seems difficult to establish whether this object has a negligible halo, since other processes such as interactions with other galaxies could also produce a one-armed structure.

Byrd et al. (1992) have suggested that the leading spiral arm in NGC 4462 is most easily understood as arising from an interaction with a smaller galaxy. In this case, their simulations indicate that the halo-to-disk mass within the optical radius must be around 8. While leading-arm spirals are rare, these sorts of detailed studies of individual galaxies may add to our knowledge of the DM fraction in spirals.

Some theoretical implications of the trends of DM fraction with galaxy luminosity are discussed in Secs. 10 and 11.

6.4 The Edge of the Halo

The difficulties in constructing reliable mass models of spirals discussed in Sec. 6.1 above illustrate the importance of detecting the edge of the halo in spirals. This is of obvious interest anyway, since it represents the most direct way of establishing the extent of dark halos and the mass contained within them, but it would also help improve constraints on halo-mass models.

If a rotation curve can be traced to the edge of the halo, the expected signature is a drop in rotational velocity. It is important to stress the difference between this situation and the drop in the inner-rotation curves of many bright spirals discussed in Sec. 6.2 above. In the latter case, the drop is due to the increase in the rotation velocity caused by the presence of the disk. In fact, it might be better to describe such rotation curves as having a "disk bump" rather than a drop. This contrasts with a rotation curve that approaches the edge of the halo. In this case, the rotation curve is expected to remain relatively flat at large radii, and then exhibit a decline.

There are a handful of examples of this kind of behavior. I mentioned in Sec. 5 that the extremely extended rotation curve of the dwarf irregular DDO 154 shows a decline at large radii (see Fig. 1). Amongst the galaxies studied by Casertano and van Gorkom (1991), NGC 3521 has a relatively flat rotation curve from about 5 to 20 kpc, but the last three points of the rotation curve show a steady decline from about 210 to 160 km s^{-1}. Similar behavior is shown by NGC 7793 (Carignan and Puche 1990a), although here the rotation curve does not appear to have a flat portion at all. However, there is a marked decline from 116 to 88 km s^{-1} that appears to occur at large enough radii that the disk bump cannot be responsible. (In any case, this galaxy is fainter than objects usually exhibiting a disk bump.)

It is conceivable that, in most galaxies, the H I does not extend to the edge of the halo. In this case, it is clearly impossible to detect the edge of spiral halos using H I measurements! However, there is some evidence that the extent and surface density of the H I and DM may be correlated (Bosma 1978: Sancisi 1983). Carignan and Puche (1990a) found that if the halo of NGC 7793 was modeled by an isothermal sphere then the ratio of H I and DM surface densities is constant with radius. A similar result was found for NGC 3109 by Jobin and Carignan (1990) and for NGC 6469 by Carignan et al. (1990). Carignan (DMW) suggests this may be a general property of spirals. Whether this is physically important is not yet clear. For instance, Lake (DMW) suggests that this may be a selection effect, arising from the detectability of H I. An increase in the H I density leads to the formation of H_2, whereas a significant decrease makes the H I undetectable.

Finally, it is worth noting that the edge of dark halos may not be a well-defined quantity. For instance, if there is a background of unclustered DM, as is the case if the Universe has the critical density required for closure, then the halos presumably merge into this background. This is one of the motivations for indirect methods to explore the extent of halos which I discuss in Sec. 8.

6.5 Dust in Spirals

Although it is usually assumed that the disks of spiral galaxies are optically thin, there have been some suggestions that dust in spirals might obscure much of the stellar light (e.g., Disney et al. 1989; Davies 1990; Valentijn 1990). This would have major implications for the deduced DM fraction in spirals. Valentijn (1990) in particular has claimed that spiral disks are opaque, so that their stellar masses are higher than usual estimates. He further argues that the exponential scale-length of the absorbing material is greater than that of the stellar disk, so that the mass-to-light ratio of spirals increases with radius.

Gonzalez-Serrano and Valentijn (1991) studied the dwarf spiral UGC 2259 and found that the rotation curve could be fit with a purely disklike mass distribution, provided absorbing material was obscuring much of the starlight. They also showed that a similar model could reproduce the rotation curve of the well-studied galaxy NGC 3198, so that a dark halo was unnecessary.

While such models can in principle explain the rotation curves of spirals, they contain several problems. As van der Kruit (1992) has emphasized, galaxies are often seen through the disks of foreground spirals, and reddened globular clusters are observed through the disk of M31. In the Milky Way, our ability to observe both North and South of the plane argues against an opaque disk. Burstein et al. (1991) and Freeman (DMW) have studied spiral-galaxy samples for dust obscuration, but find that the effect is smaller than claimed by Valentijn (1990). Moreover, Burstein et al. (1991) have pointed out that dusty spirals have similar (M/L_V) to dust-free ones. This is because the presence of dust both dims and reddens the underlying galaxy. Correcting for the dimming pushes the galaxy luminosity up so that the stellar mass is greater, but correcting for the reddening implies the true stellar population has a *lower* mass-to-light ratio. These two effects roughly cancel each other out, implying that the usual estimates of the disk mass are reasonable and that DM is required to explain most rotation curves.

It is worth pointing out that there are various arguments that suggest the dominant mass component in spirals is considerably rounder than an exponential disk (see Sec. 9 below). Thus while Gonzalez-Serrano and Valentijn's (1991) model can reproduce rotation curves, other considerations probably rule out the idea. The presence of dark halos around ellipticals also contradicts the opaque-disk model, if the popular notion that such galaxies form by the merger of spirals is correct.

7. ELLIPTICAL GALAXIES

The lack of bright elliptical galaxies in the Local Group has contributed to the difficulties in investigating their dark halos. Stellar-velocity dispersions are usually of insufficient accuracy to pin down the gravitational potential and, more importantly, only probe the inner regions of these galaxies. X-ray observations have proved the most useful means of studying ellipticals and indicate the presence of halos extending well beyond the visible parts of the galaxies. Most "polar-ring" galaxies are S0's and are discussed in Sec. 9 since they are most notable for the information they yield on the shape of dark halos. Some of the early work in this field has been summarized by Fall (1986).

7.1 X Rays and Globular Clusters

One of the first elliptical-like galaxies to be probed for DM was M87. This galaxy is actually a massive cD at the center of the Virgo cluster and is therefore not a typical elliptical. Fabricant et al. (1980) and Binney and Cowie (1981) analyzed X-ray observations of this galaxy to determine its mass profile. The underlying assumption of these and similar studies is that the X-ray emission comes from thermal gas in hydrostatic equilibrium with the local gravitational potential. This idea can be expressed through yet another form of the virial theorem:

$$\frac{dP}{dr}=\frac{-GM(r)\rho_g}{r^2}, \tag{7.1}$$

where P is the gas pressure, ρ_g is the gas density, and the other symbols have their usual meanings. Combining this expression with the ideal gas law gives

$$M(r)=\frac{-kT_g r}{G\mu m_H}\left(\frac{d\log\rho_g}{d\log r}+\frac{d\log T_g}{d\log r}\right)r \qquad (7.2)$$

(e.g., Fabricant and Gorenstein 1983), where T_g is the gas temperature. While Fabricant et al. (1980) and Binney and Cowie (1981) both found evidence for a large mass in the center of Virgo, they did not agree on whether it was associated with a dark halo around M87, or whether the mass was identified with the cluster as a whole.

This difference of opinion illustrates a problem in applying Eq. (7.2) to ellipticals. Specifically, current data provide poor information on the temperature profile of the X-ray gas. Without such information it is difficult to constrain the mass distribution. Stewart et al. (1984) attempted to overcome this problem by using both X-ray images and spectroscopy of M87 from the *Einstein* Observatory. The X-ray spectroscopy provided limited constraints on the temperature profile. These authors concluded that a dark halo with a mass of about 3×10^{13} $M_\odot$ surrounded M87, with a central density around 1.5×10^{-2} $M_\odot$ pc^{-3}.

These X-ray results subsequently received support from an analysis of the dynamics of globular clusters around M87. Huchra and Brodie (1987) obtained velocities and projected distances for some globulars in the huge system that surrounds M87 and found a dynamical mass for the galaxy of 6×10^{12} $M_\odot$ within 18 kpc of its center. If one extrapolates this dark halo assuming a mass distribution of the form $M\propto R$, the globular-cluster results converge to the X-ray results of Steward et al. (1984). Within 18 kpc, Huchra and Brodie (1987) found $(M/L_B)\sim150$. Even for stellar mass-to-light ratios at the upper end of accepted ranges, this suggests a dark-to-luminous mass ratio of at least 15.

A more recent study by Mould et al. (1990) using the kinematics of globular clusters around M87 broadly supports this conclusion. These authors find that mass models without dark halos do not fit the data. They carry out a similar study for NGC 4472 and find that, while a model without DM cannot be excluded, a more natural interpretation is that this galaxy is surrounded by a dark halo.

More representative ellipticals have also been studied using X rays. Forman et al. (1985) selected a sample of 55 galaxies detected by *Einstein* of which 39 were suitable to analyze with Eq. (7.2). Forman et al. (1985) had the usual problem with the lack of a temperature profile, and assumed that the gas in these ellipticals was isothermal. On the basis of this somewhat shaky assumption, they concluded that galaxies in their sample had dynamical masses of up to 5×10^{12} $M_\odot$. The highest dark-to-luminous mass ratios in this sample were then around 10 or more, suggesting that M87 need not be exceptional in the mass and extent of its dark halo. However, the simplifying assumption of an isothermal gas distribution could in principle lead to inflated values of the total dynamical mass.

The uncertainty in the derived mass was illustrated by a similar study of the X-ray emission from ellipticals carried out by Trinchieri et al. (1986). These authors obtained binding masses for five ellipticals, but concluded that uncertainties in the temperature profile and the assumption that the gas was in hydrostatic equilibrium produced an uncertainty of a factor of 10 in these masses.

In an attempt to obtain mass estimates from X-ray data that were less dependent on a knowledge of the temperature profile, Fabian et al. (1986) derived an expression for the minimum mass of dark halos around ellipticals. They assumed that the gas within the dark halo was confined by a hydrostatic outer atmosphere. This is not unreasonable since there is hot intracluster gas surrounding many ellipticals. It was further assumed that the gas was convectively stable and extended to a radius r_∞ where the pressure reached P_∞. These assumptions lead to a lower limit to the gravitational binding mass of a galaxy:

$$M_T\geqslant\frac{5kT_0r_0[1-(P_\infty/P_0)^{0.4}]}{2G\mu M_H(1-r_0/r_\infty)}. \qquad (7.3)$$

Here, T_0 is the temperature of the hot gas at a pressure P_0 observed at a radius r_0 in the galaxy. A measurement of typical or mean values for a given galaxy therefore yields the minimum binding mass. A knowledge of the temperature profile is less important, although steep temperature gradients can affect the results to some extent. The limit in Eq. (7.3) is equivalent to the mass required to prevent a gas at a temperature T_0 from escaping the gravitational potential of the galaxy.

Fabian et al. (1986) applied this expression to the sample of Forman et al. (1985) and found masses that were somewhat higher, thereby requiring even larger amounts of DM. They found a mean value of (M/L_B) for these galaxies of 74, with some halos having masses in excess of 10^{13} $M_\odot$. However, Fabbiano (1989) considered the effects of temperature gradients and found that much lower masses could be obtained using the expression in Eq. (7.3). Nevertheless, DM halos were still required in three of the five cases studied. Despite the uncertainties, this method does provide relatively persuasive evidence for substantial DM halos around at least some ellipticals.

Loewenstein (1992) derives constraints on the total mass distribution of NGC 4472 from both X-ray and optical data. He combines observed projected velocity dispersions for the stars and globular clusters of this galaxy with an X-ray temperature based on *Ginga* data. Curiously, the X-ray temperature is higher than expected from the velocity dispersions. It is possible that discrete X-ray sources in the galaxy are leading to an overestimate of the gas temperature. Loewenstein (1992) concludes that marginally consistent models can be constructed which require a dark-to-luminous mass ratio around 10. Further, he finds it impossible to reconcile the data with models with no dark halos. These conclusions are disputed by Bertin et al. (1992), who claim that models with and without DM can give similar X-ray temperature profiles.

Loewenstein (DMW) has applied the same technique to NGC 1399 using observations made with *BBXRT*. Again, the models require a substantial dark halo with a mass around an order of magnitude greater than the stellar component of the galaxy. Loewenstein (DMW) points out that these two galaxies are the only ellipticals that can be studied in this way at present, since X-ray spectra are not of sufficient quality to provide the required temperature information for other galaxies.

7.2 Stellar-Velocity Dispersions

The use of stellar-velocity dispersions to investigate the presence and distribution of DM in ellipticals has recently experienced a revival. This technique uses observed velocity-dispersion profiles in conjunction with the Jeans equation [Eq. (2.1) above]. Self-consistent solutions with either an assumed mass distribution or distribution function are then obtained (for a detailed discussion, see de Zeeuw 1992).

Such a study was carried out by Binney et al. (1990), who found that all the ellipticals in their sample had velocity-dispersion profiles consistent with a constant mass-to-light ratio (that is, no radial gradient in M/L). An extension of this work reached the same conclusions (van der Marel et al. 1990). These authors concluded that the galaxies showed no evidence for DM within the inner regions. It should be noted, however, that a constant mass-to-light ratio does not exclude the presence of a dark halo. If the DM has the same profile as the stars, for instance, the derived M/L will remain constant with radius, although it will be higher than that produced by the stars alone. A halo that is more extended than the stars produces an increase in M/L with radius.

It is well known that the surface-brightness profiles of the vast majority of elliptical galaxies can be fit by the $R^{1/4}$ law (de Vaucouleurs 1948; Binney and Tremaine 1987). If one accepts the hypothesis that ellipticals contain DM, this result is, at first glance, surprising. One would expect that variations in the amount and distribution of DM from one elliptical to another would lead to distortions of the $R^{1/4}$ law in many galaxies (Bertin et al. 1989). Perhaps the physical significance of the $R^{1/4}$ has been overinterpreted (cf. Makino et al. 1990). Irrespective of the *reason* for this finding, it seems likely that if DM *is* present in the inner regions of ellipticals it will require a cunning method to detect it unequivocally.

Bertin et al. (1992) attacked the problem by constructing self-consistent solutions of the two-component Vlasov–Poisson equations for elliptical galaxies embedded in dark halos. They then derived density limits on the amount and distribution of DM inside the effective radius R_e of the $R^{1/4}$ profile through the Jeans equation and the virial theorem. They found the surprising result that in a wide range of their models the $R^{1/4}$ surface-brightness profile was reproduced even with substantial amounts of DM inside R_e.

Saglia et al. (1992) have applied these techniques to ten bright ellipticals. They compared the photometric and kinematic profiles of these galaxies to their models to obtain best-fit solutions and hence constraints on possible dark halos. Saglia et al. (1992) find that inside R_e the amount of DM is not large, but is nevertheless present. Typically, the DM mass is comparable to the mass in visible material. Within R_e, characteristic values are $(M/L_B)\sim 7$ for the stellar component, compared to a total dynamical value of $(M/L_B)\sim 12$. Their models also allow the calculation of a *global* mass-to-light ratio which is much larger than the values in the inner regions of the galaxies. For one of their galaxies a mass estimate based on the kinematics of globular clusters is available and agrees well with their best-fit model.

Ford et al. (1989) used the radial velocities of planetary nebulae in the halo of NGC 5128 to study the halo kinematics. They also derived preliminary mass distributions which showed an increase in (M/L_B) from 2.4 to 10.1 over the radial range from 1.3 to 20.8 kpc. However, de Zeeuw (1992) summarizes other observations which suggest a more modest increase in this galaxy.

7.3 Gas Disks

Other methods to infer the mass distribution in ellipticals have been explored, although most give rather inconclusive results. Some ellipticals contain disks of ionized gas which can be exploited for this purpose (e.g., de Zeeuw 1991). Caldwell et al. (1986) studied such a disk in NGC 7097 and found that the mass-to-light ratio increased from less than unity in the galaxy center to over 3 at 3.5 kpc. This requires DM, but assumes that the gas in the disk is on circular orbits. Bertola et al. (1991) carried out a similar study of NGC 5077 and concluded that circular orbits required the presence of DM. However, they also showed that the motions could be understood without resorting to a dark halo if the assumption of circular motions was dropped.

Some ellipticals contain disks of cold H I gas (e.g., van Gorkom 1992). The H I typically extends much further than the ionized gas disks mentioned above and can also be used as a probe of DM (Lake et al. 1987). For five such galaxies, Kent (1990) compared central mass-to-light ratios based on stellar-velocity dispersions with values derived from the gas disks. Only IC 2006 showed an increase in M/L. This galaxy is surrounded by a counter-rotating ring of H I. Schweizer et al. (1989) find that (M/L_B) rises from around 5 in the center to 16 at the ring radius, assuming the ring is circular. This suggests the presence of a dark halo with about twice as much mass within this radius as the stellar component. However, Lees (1991) finds the increase can be reduced if the orbits are elliptic and claims that such orbits along with a triaxial halo provide a better fit to the data.

The evidence for DM in ellipticals is compelling, although not as overwhelming as is the case for DM in spirals. The problem is that the techniques for probing DM in ellipticals tend to be model dependent, so it is often possible to find gravitational potentials that are consistent with the data and which do not require dark halos. However, the above results suggest that it is extremely likely that elliptical galaxies are surrounded by significant amounts of DM.

8. GALAXIES IN PAIRS, GROUPS, AND CLUSTERS

In this section I review evidence for the existence and extent of DM halos around galaxies that are gravitationally bound to other galaxies. The location of such galaxies allows somewhat different methods to be employed in investigating their halos. Since this review is concerned with the specific issue of DM in galaxies, the question of the amount and distribution of DM in groups and clusters is only briefly mentioned here. For more details of issues relating to DM in groups and clusters of galaxies, see, for example, Heisler et al. (1985), West and Richstone (1988), Fitchett (1990), and Beers et al. (1991).

8.1 Binary Galaxies

Bound pairs of galaxies offer the attractive possibility of obtaining estimates of halo masses at greater distances than are usually accessible to H I rotation-curve measurements. In practice, however, such observations have proved rather difficult (Page 1962; Trimble 1987 and references therein). Since the geometry of the orbit of a given binary pair is unknown, it is impossible to translate the projected velocity difference and separation into orbital velocity and physical separation. Statistical methods have therefore usually been applied to a large sample of binary galaxies. Eliminating chance superpositions and brief encounters from the sample of genuine bound pairs is a major difficulty. Despite these problems, some interesting results have been obtained.

White (1981) described the minimum requirements for deriving an indicative mass from a sample of binary galaxies. These criteria were applied by White et al. (1983) who found dark-to-luminous mass ratios higher than those usually attributed to individual galaxies. (This, of course, was not surprising, since the study probed dark halos to greater radii than investigations of individual galaxies. In fact, these authors noted that their results were consistent with extrapolations of observed rotation curves.) Interestingly, White et al. (1983) found that the mass-to-light ratio of their galaxies increased with decreasing luminosity L:

$$M/L \approx 47 \pm 13 \left(\frac{r}{100\ \mathrm{kpc}}\right)\left(\frac{L}{L_*}\right)^{-3/4}, \qquad (8.1)$$

assuming circular orbits and $h=0.5$, where r is pair separation and L_* is the knee of the galaxy-luminosity function. This is in agreement with the trend for spirals discussed in Sec. 6 above.

Lake and Schommer (1984) used a similar method to study nine pairs of dwarf-irregular galaxies. They found extremely high M/L values, ranging from 20 to 5000 for separations between 40 and 850 kpc, which fit in fairly well with the relationship given in Eq. (8.1). However, as Lake and Schommer (1984) acknowledged, applying statistical arguments to such a small sample is hazardous.

Karachentsev (1983,1985) studied large samples of binary galaxies to derive masses for galaxy pairs. He found little evidence for substantial amounts of DM around these systems. Indeed, he argued that the amount of DM in the halos around these objects was no more than a factor of 2 greater than the dark mass within R_{25}. Karachentsev (1985) noted that this was a rather surprising result, particularly in view of the fact that some of the galaxies in his sample were known to have flat rotation curves.

A different approach was adopted by van Moorsel (1987). He studied 16 pairs of galaxies using H I measurements to obtain rotation curves for individual galaxies as well as the projected velocity separation of each pair. He concluded that the dark halos of the galaxies in his sample extended well beyond the H I rotation curves, and that there was typically three times as much DM present in these systems as could be accounted for by the rotation-curve measurements. He also suggested that the data were consistent with a common DM envelope surrounding galaxy pairs.

More recent studies have highlighted the difficulties involved in using binary galaxies for mass determinations. Sharp (1990) concluded that statistical approaches to derive masses from binary pairs were unable to provide reliable results. He illustrated this by comparing previous studies by different workers who obtained dramatically different mass estimates. Sharp (1990) found that the causes of these discrepancies included different methods of analysis, none of which could be shown to be objectively superior. Confusion was also introduced by the fact that many galaxies in pairs are interacting. These gloomy findings were somewhat tempered by Sharp's (1990) suggestion that detailed analysis and modeling of individual pairs could yield useful dynamical masses.

Further concerns were expressed by Schneider and Salpeter (1992). They showed that if the projected separation for including galaxies in a binary sample was fixed at too low a value, then artifacts in the velocity-separation distribution could be introduced. The troublesome "peak" at 72 km s^{-1} in many such samples is probably the result of such a selection bias, unless one prefers Tifft's (1976) suggestion that redshifts are quantized. However, in order for such a peak to be produced by selection procedures, the degree of incompleteness in extant binary samples must be high (Schneider and Salpeter 1992). This result casts serious doubts on the validity of mass determinations based on such samples.

Instead of directly estimating masses of binary galaxies, Charlton and Salpeter (1991) used the distribution of projected separations to study the extent of dark halos. In low-density environments, they found an excess of pairs with low-velocity separations out to projected spatial separations as great as 1 Mpc. Moreover, the distribution of projected separations was featureless from small distances out to 2 Mpc. This is somewhat surprising, since galaxy mergers are expected to deplete the number of pairs at separations less than the characteristic halo radius. Charlton and Salpeter (1991) suggested that extremely extended halos, with radii around 1 Mpc, were consistent with these observations. Alternatively, they argued that galaxies in low-density environments may be surrounded by a common DM envelope.

One problem with such large halo radii is that, unless the halo-density profile does something pathological, the mean density is extremely low. Thus halos with radii around 1 Mpc would not have virialized by the present epoch (Ashman 1991). The common-envelope idea may also have problems, since a smooth DM "superhalo" would simply raise the background density. In this case, halos associated with individual galaxies would be of a more conventional size, thereby reintroducing the depletion-by-merger problem that Charlton and Salpeter (1991) were attempting to overcome. Numerical simulations may clarify this issue.

8.2 Galaxies in Groups

Erickson et al. (1987, 1990) adapted van Moorsel's (1987) method described above in order to study galaxies in small groups. Specifically, they obtained H I observations of spiral galaxies that were surrounded by one or more gas-rich satellites. Dynamical masses for the primary galaxies were obtained from H I rotation curves, and a statistical measure of the mass beyond the rotation curves was obtained from the projected distances and velocity separations of the galaxies. On average, the satellites probed distances about three times greater than the rotation curves.

Erickson et al. (1987, 1990) concluded that the halos of the primary spiral galaxies contained about three times as much mass as the dynamical mass of the spiral disks. They argued that this result favored small halo masses. However, it is important to notice that these authors compared the halo masses probed with the satellites to *dynamical* disk masses. In other words, their disk masses are a combination of the mass of the stellar disk and the halo mass within the last measured point of the rotation curve. Since the mean distance between primaries and satellites is about three times the average extent of their rotation curves, these results actually support extended, roughly isothermal halos.

Erickson et al. (1990) further argued that the primary halos were unlikely to be very extended on the grounds that the satellites showed little evidence for major tidal damage. Their preferred halos consequently had radii of about 60 kpc for the primary spiral galaxies in their sample. However, observations of the satellites of the Milky Way challenge this assertion. There is good evidence that the Galactic halo extends to at least 100 kpc. The Magellanic Clouds, which are similar to the satellites of other galaxies considered by Erickson et al. (1990), are currently well within this radius. While the Magellanic Clouds are a little ruffled, and may even be fragments of a disrupted galaxy (e.g., Mathewson et al. 1986), they are still identified as individual objects.

A similar study has been carried out by Zaritsky et al. (1992). They have a larger sample of satellite galaxies relative to Erickson et al.'s (1990) work and, more importantly, a greater mean separation of primaries and satellites which allows the halos of spirals to be probed to greater distances. Zaritsky et al. (1992) conclude that the spirals in their sample are typically surrounded by about $10^{12}\ M_\odot$ of DM within about 200 kpc. This is comparable to the estimated mass of the Milky Way halo discussed in Sec. 3.

In the M96 group of galaxies in Leo, there is an enormous ring of intergalactic gas surrounding the central pair of galaxies, M105 and NGC 3384 (Schneider et al. 1989). In order for the ring to survive, Schneider (1991) has argued that it must lie outside the dark halos of M105 and NGC 3384. This limits their halo radii to about 60 kpc, which is consistent with the combined dynamical mass of the pair of $6\times10^{11}\ M_\odot$ inferred from the ring kinematics. This is only twice the mass inferred for the two galaxies from their rotation curves, corresponding to a total mass-to-light ratio of 25. Such a low value is a little unusual, although it is possible that the location of these galaxies in the center of a group may have led to the truncation of their halos (see also Sec. 8.3 below).

Puche and Carignan (1988) carried out a study of the Sculptor group of galaxies. They adopted a novel method of ascertaining group membership by applying the virial theorem to a region of the sky centered on Sculptor. Puche and Carignan (1988) calculated the virial mass of the group from all galaxies in this region and then rejected galaxies that were driving the derived mass to exceptionally high values. They found that the virial mass converged to a value around $2\times10^{12}\ M_\odot$ when five group members remained. Puche and Carignan (1988) concluded that only these galaxies constituted a physically bound group, and that the remaining three galaxies previously suspected of group membership were interlopers.

Individual rotation curves were obtained for the five galaxies identified as members of Sculptor (Carignan and Puche 1990a,b; Puche et al. 1990; Puche et al. 1991; Puche, et al. 1991). Puche and Carignan (1991) used these measurements to obtain the sum of the masses of the individual galaxies. They found a total mass in the galaxies of $2\times10^{11}\ M_\odot$, and concluded that if the halos extended ten times further than the measured curves, then all the DM in this group could be associated with individual galaxies. This requires that the halos have an average radius of 42 kpc. This low value reflects the relatively low M/L_B of 83 ± 10 that Puche and Carignan (1988) derive for this group. Dynamical estimates in other groups and clusters typically give values of $M/L_B\approx200$–$500h$.

One concern with this analysis is that the overdensity for the group derived by Puche and Carignan (1988) is very low. This can be quantified by recalling that the density of fluctuations at turnaround is $9\pi^2/16$ times the critical background density at that epoch (e.g., Gott and Turner 1977). The virialization of such an overdense region increases its density by another factor of 8, during which time the density of the Universe has decreased by a factor of 4 (higher if the density of the Universe is less than critical). For an object such as a galaxy halo to have virialized by the present epoch, it must therefore have a density of at least $18\pi^2$ times the critical background density (cf. Ashman and Carr 1988; Lake 1990b; Ashman 1991).

Translating this argument into something more manageable, I obtain

$$\rho > 4 \times 10^{-27} h^2 \text{ g cm}^{-3}. \tag{8.2}$$

Only halos with densities satisfying Eq. (8.2) have virialized by the present epoch. It is risky at best to apply the virial theorem to systems of lower density. The results of Puche and Carignan (1988) imply that the mean density of the Sculptor group is no more than about 5×10^{-29} g cm^{-3}, so that Sculptor does not appear to be virialized. Under certain circumstances, application of the virial theorem to an unvirialized system can underestimate its mass. Further, the procedure for determining group membership relies on throwing out galaxies that give a large value for the group mass. It is therefore conceivable that the mass-to-light ratio of Sculptor is somewhat higher than Puche and Carignan (1988) claim.

Equation (8.2) also indicates that merely requiring that the crossing time of a system is less than the age of the Universe is *not* a sufficient condition to apply the virial theorem. In fact, since the crossing time scales as $\rho^{-1/2}$, the above considerations imply that the crossing time of a system must be less than about a tenth the age of the Universe in order for the virial theorem to be applied.

8.3 Galaxies in Clusters

The halos of galaxies in clusters could have been modified by the dense and perilous environment where close encounters of galaxies may be frequent. Studying such halos may therefore yield valuable information about the formation and evolution of clusters. Dynamical considerations suggest that all of the DM in clusters is unlikely to be associated with individual galaxies. If this were the case, dynamical friction would have led to the most massive galaxies being dragged into the cluster center. Some mass segregation of this kind is observed, but the degree suggests that most DM is distributed smoothly in many clusters (White 1977). The DM may have been associated with the galaxies originally, in which case tidal disruption of DM halos could produce a smoother DM distribution by the present epoch (Richstone 1976). West and Richstone (1986) have presented *N*-body simulations which show that the removal of DM halos from galaxies may be a natural consequence of cluster formation.

Some evidence for stripped halos around spirals in clusters is provided by Whitmore et al. (1988). They found that galaxies close to the center of clusters typically had flat or falling curves, whereas those in the outer regions of galaxy clusters have flat or rising curves. This is the sort of effect one would expect if the cluster environment leads to halo stripping (see also Whitmore 1990).

The correlation between rotation curve shape and distance from the cluster center is less apparent in other samples (Distefano et al. 1990; Amram et al. 1992a,b). Whitmore et al. (1992) suggest this discrepancy might arise because these samples contain a large number of galaxies at distances beyond 1 Mpc from the cluster center. If the physical conditions responsible for truncating halos are more effective within 1 Mpc, as is physically plausible, these samples would be expected to show weaker correlations. Whitmore et al. (1992) also note that using galaxies with extended halos for these studies (i.e., extended rotation curves) could also bias the results, since the survival of extensive gas disks probably only occurs in galaxies that have *not* undergone much tidal stripping.

Bird et al. (1992) and Bird (1992) have studied the DM distribution in the Hercules cluster of galaxies. Using H I observations of spirals in this cluster and by applying statistical mass estimators, they derive $M/L \approx 300h$ for the cluster as a whole. These authors also have H I linewidths for some of the spirals in the cluster. Bird et al. (1992) conclude that the halos of the galaxies, if isothermal, need to extend to about 15 times the distance of the measured rotation curves to account for all the DM in Hercules. This corresponds to halo radii around 300 kpc. Such halos would be larger than those inferred around isolated galaxies. Moreover, as Bird et al. (1992) point out, 300 kpc is uncomfortably close to the typical separation between galaxies in Hercules.

These kinds of studies have the potential for constraining the dark halo radius of cluster galaxies, but are currently somewhat limited by the complex problem of deriving reliable mass estimates for the clusters themselves. This problem is beyond the scope of the present review (see, however, papers in the proceedings edited by Fabian 1992, as well as the literature cited at the beginning of this section).

9. THE SHAPE OF THE DARK HALOS

Many of the models of dark galactic halos described in previous sections assume that the density profile can be described by some kind of isothermal sphere. As discussed in Sec. 6, steeper density profiles are also consistent with much of the data, but there is the more radical possibility that halos are significantly flattened. Some degree of flattening would not be a great surprise, since stellar systems exhibit varying degrees of oblateness or triaxiality. However, the difficulties in pinning down the mass distribution of halos discussed in earlier sections suggests that establishing the shape of halos is an even bigger problem. Despite the magnitude of the task, some progress has been made.

An early argument for the existence of dark halos, and spherical halos in particular, was given by Ostriker and Peebles (1973). They suggested that dark, spherical mass distributions around spirals would suppress bar instabilities in their stellar disks. This argument was undermined by Kalnajs (1983), who showed that a central bulge or hot disk could do the same job just as effectively (see also Sellwood 1985). Monet et al. (1981) argued that the roundness of the Galactic bulge implied the presence of a roughly spherical dark halo around the Milky Way. Hartwick (1987) reached a similar conclusion from the spatial distribution of RR Lyraes and metal-poor globular clusters in the Galactic halo. Dupraz and Combes (1986) proposed that the shapes of shells observed around some galaxies could be used to investigate the halo flattening.

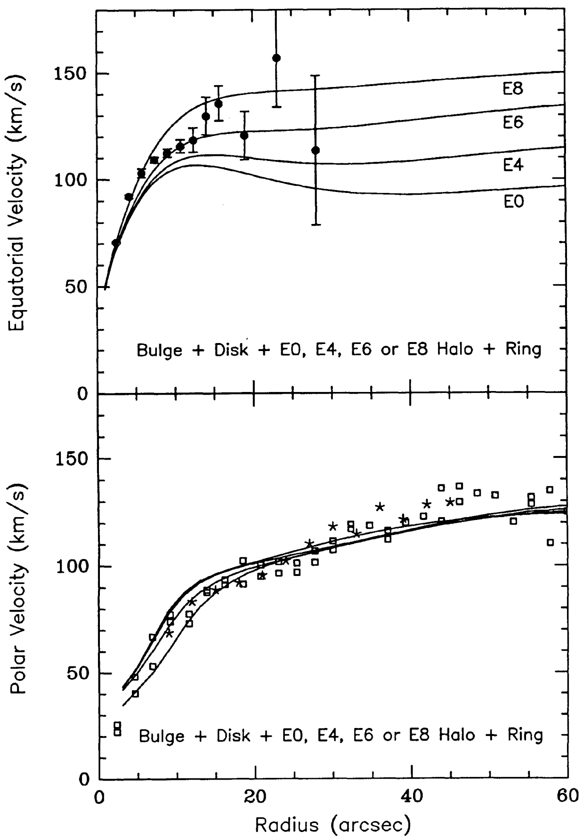

FIG. 3—Model fits to the equatorial disk (upper panel) and polar ring (lower panel) of the polar-ring galaxy NGC 4650 A. The upper panel shows the predicted velocities for dark halos of different flattenings. The E6 halo is the preferred solution. Figure courtesy of P. Sackett.

However, N-body simulations that reproduce such shells in galaxy mergers show that the shell shape probably does not reflect the halo shape (Hernquist and Quinn 1988). Twisted velocity fields in the H I disks of spirals may also reflect a nonspherical halo, although to definitively determine the halo shape it is necessary to decouple kinematic twists from possible structural twists. Rotation-curve modeling in spirals can provide some shape information (Carignan, DMW), but high-quality, extended H I curves are needed. The shape of the bulge in spiral galaxies may reflect competition between the flattening effects of the disk potential and the rounder halo, but the bulge shape is also sensitive to rotation and anisotropic velocity dispersion.

9.1 Polar-Ring Galaxies

The method that has provided the most clear cut evidence for flattened halos uses polar-ring galaxies (PRGs). A catalog of such objects was compiled by Whitmore et al. (1990). The main drawback of such objects is that they are rather rare, so few have been studied in detail. Nevertheless, given the difficulties with other techniques, they are a welcome tool for probing dark halos.

Schweizer et al. (1983) and Whitmore et al. (1987) pioneered early attempts to use the kinematics of polar rings to infer something about the halo shape. Subsequently, Sackett and Sparke (1990) developed a method which uses all the observational data in deriving a realistic gravitational potential. They applied their technique to the PRG NGC 4650A. This galaxy also has a planar disk, so that there is velocity information in two planes. Consequently, the overall potential, and thus the shape of the halo, is reasonably well constrained. Sackett and Sparke (1990) fit the two rotation curves with a model consisting of a bulge, disk, axisymmetric dark halo, and massive polar ring. They concluded that the halo of NGC 4650A probably had a flattening of between E3 and E7, although a spherical halo could not be ruled out. [Recall that the designation En is defined so that $n=10(1-b/a)$, where a and b represent the major and minor axis, respectively.] More recent work (Sackett, DMW) appears to exclude a spherical halo and points to an E6 halo surrounding NGC 4650A (see Fig. 3). However, it should be stressed that NGC 4650A has the flattest halo of the three galaxies originally studied by Whitmore et al. (1987), so that further studies of more of these objects would be valuable.

Sackett (1991) has pointed out that the full projected-velocity field of the ring around NGC 4650A and similar galaxies may be a particularly powerful diagnostic. The noncircularity of polar orbits leads to a misalignment between kinematic and morphological axes (cf. Teuben 1991 and references therein). This kinematical twisting acts as a probe of the underlying potential. The principal difficulty may lie in separating such twists from physical warps, but studying kinematic twists has the potential to yield shape information.

At least one galaxy halo appears to be appreciably flattened. Unfortunately, PRGs are unusual objects and their halos may be atypical. For instance, they have clearly suffered some kind of merger, and this could have given rise to a flattened halo. Alternatively, it may require a flattened halo to define a plane dynamically to ensure that the ring that forms is polar at all. In this case the scarcity of PRGs may argue for the majority of halos to be spherical. It is therefore necessary to complement studies of PRG galaxies with work on the shapes of halos around other types of galaxy.

9.2 Warped and Flaring Disks

Constraining the shape of the halos of ellipticals using gas disks was briefly mentioned in Sec. 7. Lees (1991) has argued that the twisted disk in the elliptical galaxy IC 2006 is indicative of a triaxial halo. Warps in spirals have also been used to constrain the concentration of their dark halos (Sec. 6.1). However, other techniques have also been pursued which yield shape information. Sparke and Casertano (1988) showed that both the concentration and oblateness of spiral-galaxy halos could be constrained by modeling the shape of the warp. This work has been extended to include time evolution of the gas disk by Hofner and Sparke (1991). Their results indicate moderate flattening in the galaxies they have studied. In NGC 2903, for instance, the halo must be flatter than E2.

Dynamical arguments further suggest that concentrated dark halos should inhibit warps in disk galaxies (Sparke and Casertano 1988). This prediction has gained support from spiral-galaxy mass modeling, which indicates that spirals with small halo core radii rarely have warps (Bosma 1991; Bosma, et al. 1988).

Steiman-Cameron et al. (DMW) have taken a different approach. They use galactic accretion disks to probe the potential of the dark halo. The idea is to model the accretion of a satellite in order to understand how the final state of the gas disk reflects various parameters, including the shape of the halo (see Steiman-Cameron and Durisen 1990). Under certain conditions, analytic solutions to the problem may be obtained (Steiman-Cameron and Durisen 1988). So far, the results indicate fairly spherical halos. For instance, for the S0 galaxy NGC 4753, Steiman-Cameron et al. (DMW) find a ratio for the minor to major axes of the halo of between 0.84 and 0.99.

Steiman-Cameron (1991) has also emphasized that if twists in disks are caused by differential precession, then the sense of the twist (whether it leads or trails the rotation) reveals whether the mass distribution is oblate or prolate. In the S0 galaxy NGC 4753, the halo proves to be oblate. On the other hand, NGC 5033 and 5055 have prolate halos.

Teuben (1991) notes that warped disks are more easily understood if the surrounding dark halos are triaxial. The ubiquity of warps (Bosma 1991) then supports the notion that many dark halos are triaxial. Teuben (1991) shows that fitting tilted-ring models (Begeman 1987, 1989) to gas disks provides a method of inferring the presence of triaxial potentials. Such models reveal deviations from circular motion which are indicative of nonaxisymmetric potentials. However, there are other mechanisms that can excite and preserve warps that do not necessarily require triaxial halos (e.g., Bertin and Casertano 1982).

Blitz and Spergel (1991) suggest that a rotating triaxial halo can explain observed asymmetries in the H I distribution of the Milky Way. They also find that the dark halo is *nearly* axisymmetric at large radii, with an axis ratio of $b/a > 0.87$.

Observations of edge-on spirals indicate that the scale height of most gas disks increases with radius. This flaring is not surprising since the velocity dispersion of the gas remains constant with radius, whereas the gravitational potential of the stellar disk declines. However, the H I disk is also responding to the potential of the halo, so in principle mass modeling of the stellar disk and the gas disk can provide information about the shape of the halo.

Maloney (DMW) is investigating this technique. Unfortunately, his results indicate that the thickness of the H I layer is rather insensitive to the shape of the halo. Thus, while halos as flat as the disk can be ruled out, more detailed information cannot be obtained. Prospects are better for the Milky Way where one can incorporate estimates of the gas density of the disk to constrain halo models.

9.3 *N*-body Experiments

N-body simulations of the dissipationless formation of halos have been used to study halo shape. Dubinski and Carlberg (1991) found that dissipationless collapse gave rise to halos that were typically quite flattened. Specifically, they found that the mean values of the axis ratios were $\langle c/a \rangle = 0.50$ and $\langle b/a \rangle = 0.71$, where *a, b,* and *c* are the axes of a triaxial ellipsoid. Thus, not only were the halos flattened, they were also strongly triaxial. Similar numbers of oblate and prolate spheroids were produced by these simulations.

Frenk et al. (1988) also found a preponderance of flattened halos in their simulations. However, while Katz (1991) found mainly triaxial halos in his dissipationless *N*-body simulations, the inclusion of a dissipative gaseous component led predominantly to oblate halos (Katz and Gunn 1991). Nevertheless, flattened halos appear to be a generic feature of such simulations.

Obtaining an observed distribution of halo shapes is still a long way off, but the results of Dubinski and Carlberg (1991) may be confronted with observation quite soon. One of the results of their simulations was that dissipationless collapse does not produce halos flatter than E6. Thus detecting halos more flattened than this would represent powerful evidence in favor of baryonic DM. The main concern is that such observations are only likely for rather unusual galaxies and, as noted above, it would be dangerous to draw conclusions about the shape and nature of halos from such special cases. Moreover, Merritt (1991) has raised the possibility that a bending instability may disrupt stellar systems that are dynamically hot and flatter than about E6.

One further curious result of Dubinski and Carlberg's (1991) study is that dissipationless collapse produces fewer round systems than occur in the distribution of elliptical galaxies. It may therefore be the case that under certain circumstances dissipation can actually make the resulting systems rounder rather than flatter as one would intuitively expect. Warren et al. (1992) have found better agreement between their *N*-body simulations and more recent observed elliptical shapes. However, Ryden (1992) finds that ellipticals are on average rounder than clusters of galaxies, suggesting that if clusters form without dissipating then ellipticals must have undergone dissipative collapse. While this introduces an added complication, it does not alter the conclusion that very flat halos can only form if there is substantial dissipation. An unambiguous detection of an E8 halo would therefore be strong evidence for baryonic DM.

10. DARK-MATTER SEARCHES AND CONSTRAINTS

The arguments that constrain the nature of the DM are nearly as varied as the DM candidates that have been proposed over the years. Similarly, attempts to detect DM involve a wide range of experimental techniques. The field has grown to such an extent that a recent major workshop was devoted entirely to baryonic DM (Lynden-Bell and Gilmore 1990), while discussions of experiments to detect nonbaryonic DM candidates are assigned a good deal of time at cosmology meetings. The treatment given here of some of these issues is necessarily brief and an emphasis is placed on the galactic aspects of the problem.

Perhaps the most fundamental question concerning the DM in galaxies is whether it is baryonic or nonbaryonic. Standard primordial nucleosynthesis calculations indicate that the baryonic density of the Universe Ω_b is around $0.015h^{-2}$ (Walker et al. 1991; Peebles et al. 1991). The most recent study incorporates a Monte Carlo analysis to estimate the uncertainties in the predicted abundances of light elements (Smith et al. 1992). When compared with observations, this work yields

$$0.01 < \Omega_b < 0.09, \qquad (10.1)$$

although inhomogeneities in the early universe allow a somewhat greater range (see below).

According to Efstathiou et al. (1988), the mass-to-light ratio of galaxies is related to the density parameter by

$$\left(\frac{M}{L_B}\right) \approx 1600\Omega h. \qquad (10.2)$$

Thus for typical galactic mass-to-light ratios summarized in previous sections, all the DM in galaxies could be baryonic. These results also indicate that much of the baryonic material in the Universe remains undetected (see also Carr 1990; Walker et al. 1991; Persic and Salucci 1992). However, these baryons need not make up the DM in galactic halos, but could instead be in a uniformly distributed intergalactic medium. Thus nucleosynthesis calculations tell us nothing about DM in galaxies other than it could be baryonic, nonbaryonic, or a mixture of the two.

10.1 Nonbaryonic Dark Matter

Much of the interest in nonbaryonic DM candidates was sparked by theoretical arguments that favor a universe with the critical density (e.g., Guth 1981; Steinhardt 1982; Peebles 1988; Schramm 1991). Despite attempts to modify standard nucleosynthesis calculations by including inhomogeneities and diffusion processes in the early universe (Applegate and Hogan 1985; Alcock et al. 1987; Malaney and Fowler 1988), it has proven difficult to obtain $\Omega_b = 1$ and still satisfy constraints from light-element abundances (e.g., Hogan 1990; Malaney and Mathews 1992). Thus a universe with $\Omega = 1$ requires nonbaryonic DM, which raises the possibility that dark halos are made of such material.

Nonbaryonic candidates are usually classified as either hot or cold (cf. Bond and Szalay 1983). In a universe dominated by hot DM, clusters of galaxies form first, whereas cold DM universes form galaxies by hierarchical clustering of smaller units. ("Seeded" hot DM models, however, produce galaxies before clusters; see, e.g., Turok 1991 and Cen et al. 1991). Pure hot DM has fallen from favor for a number of reasons, such as evidence that galaxies form before clusters and apparent disagreements with observations of large-scale structure. Cold DM also has problems, but its popularity has proved more resilient.

Constraints on nonbaryonic DM candidates are obtained in two ways: direct limits from laboratory experiments, and indirect astrophysical constraints. Information is also obtained as a spin-off from some accelerator experiments. Laboratory experiments are often aimed at finding specific candidates, but in practice they tend to constrain the parameter space of hypothetical DM particles. Recent discussions on the particle physics motivations for nonbaryonic DM candidates, as well as the experimental techniques and results in this field, have been given by Krauss (1990, 1991), Primack et al. (1989), and Turner (1992) amongst others (see also papers in the proceedings edited by Audouze and Tran Thanh Van 1988 and Holt et al. 1991).

Many of the cold DM candidates fall under the general category of weakly interacting massive particles (WIMPs). Results on the Z boson resonance place the most stringent limits on the properties of WIMPs. Combined with direct search experiments, they rule out the heavy neutrino as a viable cold DM candidate (Krauss 1991). Apparently, these limits also rule out the sneutrino and make life difficult but not impossible for the neutralino. In other words, certain WIMPs have been excluded, whereas others remain possible candidates. Importantly, Krauss (1991) notes that these constraints demand that WIMPs have properties that will make them considerably harder to detect than earlier ideas suggested.

One astrophysical technique of detecting WIMPs is by detecting γ rays or other photons that may be produced when WIMPs annihilate. The flux from a smooth halo is very low, but Lake (1990c) pointed out that if the DM has a lumpy distribution, as is probable in many cosmological models, then the signal may be detectable. Annihilations in the Earth also produce detectable signals and may prove a better way of constraining WIMP properties (Kamionkowski 1991).

One of the most popular cold DM candidates is the axion. The upper bound on its mass is about 10^{-3} eV, based on observations of neutrinos from SN 1987A (e.g., Raffelt and Seckel 1988). The lower bound used to be around 10^{-5} eV, but there has been some recent discussion that this may have to be raised (Davis 1986; Wilczek 1992). It is therefore possible that axions may be ruled out, but there is little consensus at the moment on the lower-mass limit.

Theorists are clearly having their choices of cold DM candidates trimmed by such experiments. Hot DM is having even more trouble, primarily because of astrophysical constraints. The high DM densities inferred in some dwarf spheroidal galaxies such as Draco and Ursa Minor are particularly useful in this regard. I noted in Sec. 4 that the central density in these objects is not well determined, but that there are firm lower limits based on the virial theorem. Tremaine and Gunn (1979) showed that considerations of the phase-space density of dark halos provides a lower limit to the mass of a hot DM particle such as the neutrino. (This is a "light" neutrino rather than the cold DM heavy neutrino mentioned above.)

For the neutrino or similar particle to contribute a significant DM density, it must have a mass around 30 eV. A greater mass leads to a density in excess of the critical density required to close the Universe. If such particles constitute the DM in an isothermal dark halo, the neutrino mass must satisfy

$$m_\nu \geqslant 170 g_\nu^{-1/4} \left(\frac{r_c}{\mathrm{kpc}}\right)^{-3/4} \left(\frac{\rho_0}{0.1\ M_\odot\ \mathrm{pc}^{-3}}\right)^{-1/8}\ \mathrm{eV} \tag{10.3}$$

(e.g., Spergel 1991), where r_c is the core radius of the DM halo, ρ_0 is the central DM density, and g_ν is a parameter of order unity.

If the halos around Draco and Ursa Minor are made of neutrinos, Eq. (10.3) and current limits on ρ_0 require a core radius 100 times that of the stellar distribution or an enormous dark mass within the core (Gerhard and Spergel 1992). By considering the time scale for dynamical friction to drag such objects into the Milky Way, Gerhard and Spergel (1992) conclude that, if the halos of Draco and Ursa Minor are made of neutrinos, then $m_\nu \geqslant 80$ eV. Such a mass is well above the value that produces closure density.

There have been attempts to circumvent these limits using highly anisotropic distribution functions for the neutrinos. Gerhard and Spergel (1992) argue that such distributions are unstable, so that the limit of Tremaine and Gunn (1979) is still valid. This appears to rule out neutrinos as viable candidates for the DM in the halos of Draco and Ursa Minor. However, the high central densities of these objects also require that the halos virialized at very early epochs, at least if the DM is dissipationless. Indeed, their formation would have occurred at higher redshifts than expected for universes dominated by cold DM (Lake 1990b). If one wants to overcome the early-formation epoch, a solution is to suppose that DM in these two dwarfs dissipated, which would require it to be baryonic (Kormendy 1990; Lake 1990b). Alternatively, as mentioned in Sec. 4, there have been suggestions that there is no DM in dwarf spheroidals.

A very specific nonbaryonic DM candidate is a neutrino-like particle that decays to produce hydrogen-ionizing photons. Sciama (1988) showed that such photons could explain the ionization of Ly-α clouds and the IGM at high redshifts. Sciama (1990a) also showed that if such photons were responsible for the observed ionization of H I clouds in the Milky Way, then the characteristics of the decay were tightly constrained. In particular, the particle would decay into a photon with an energy close to 14 eV. This picture also required a fairly flattened halo for the Galaxy (Sciama 1990b). Salucci and Sciama (1990) showed that such a mass model agreed well with observations of the Milky Way rotation curve.

Davidsen et al. (1991) used the *Hopkins Ultraviolet Telescope* to search for the predicted spectral signature in the cluster A655. If the DM in this cluster was comprised of the decaying DM particles, then the 14 eV line was well within the sensitivity of the instrument. However, the line was not detected. A nondetection was also reported by Fabian et al. (1991) from *IUE* observations of the quasar 3C 263 which lies at the center of a moderately rich cluster. However, Fabian et al. (1991) suggested that the spectral line could be absorbed by cold gas clouds such as those found in some nearby clusters (White et al. 1991). Another argument to rehabilitate the model is that the DM in the center of clusters is partly baryonic (as suggested by results described below), so that the strength of the 14 eV line is less than predictions which assume all the cluster DM is comprised of decaying particles.

10.2 Baryonic Dark Matter

Instead of these exotic candidates, it is possible that dark halos are made up of ordinary baryonic material. In this case, there are various constraints on the form that such baryonic DM can take. Most of these constraints come from considerations of the Milky Way halo. The majority of studies have concluded that the only viable candidates are brown dwarfs and sufficiently massive black holes (e.g., Carr 1990; De Rújula et al. 1992). Hot gas in halos would generate too many X rays (Hegyi 1984), whereas cold gas can be ruled out immediately since it would tend to settle in a disk. Hydrogen snowballs (solid hydrogen objects with subplanetary masses) can also be ruled out (Hills 1986). M dwarfs are excluded by source-counts limits (Gilmore and Hewitt 1983). More recent work by Richstone et al. (1992) illustrates that very few stars at the low-mass end of the visible stellar spectrum are present in the Milky Way halo. Other stellar remnants conflict with nucleosynthesis and background-light constraints (McDowell 1986; Hegyi and Olive 1986).

The brown-dwarf and black-hole options have often been criticized on the grounds that observations of current star formation do not find significant numbers of such objects. This is hardly surprising. We know that there is very little DM in the disk of the Milky Way (cf. Sec. 2 above), so, without making any further observations, we also know that there is very little DM in current star-forming regions. One *cannot* draw detailed conclusions about the nature of dark halos from studies of star formation in the disk of the Milky Way. It seems to me that this point has been misunderstood, since one still sees papers which claim to contain dreadful news for brown dwarfs as DM candidates due to the lack of evidence for such objects in star-forming regions. Even more extraordinary are the aspersions cast on brown dwarfs based on the lack of such objects in binary-star systems with visible primaries. Limits on brown dwarfs in binaries have little to do with a hypothetical dark halo of brown dwarfs in the Milky Way, since this would require the $10^{11}\ M_\odot$ of DM in the Milky Way halo to be accompanied by visible binary companions with a total mass around $10^{12}\ M_\odot$! (Admittedly it would be reassuring to find *some* brown dwarfs, just to determine whether such objects can form at all, but the above observations do not provide any direct constraints on the nature of the DM in galactic halos.)

The easiest way of putting a lot of mass into dark objects is to suppose that, at earlier epochs, the stellar IMF was skewed to either low- or high-mass objects. In either case, one simply needs to truncate the IMF. For instance, imposing an upper mass around the hydrogen-burning limit of 0.08 $M_\odot$ ensures that all objects that form are brown dwarfs. In the high-mass case, truncation prevents the formation of stars that will produce too many metals or still be on the main sequence today. The pollution problem requires that only stars with masses greater than about 200 $M_\odot$ form. Such objects collapse to black holes without ejecting too many metals (Carr et al. 1984; Carr 1990).

Ryu et al. (1990) resurrected an alternative to brown dwarfs or black holes. They pointed out that white dwarfs have the advantage of being known to exist. The problem is that to avoid forming M dwarfs that would still be around today, and more massive stars that would pollute the Milky Way with metals, Ryu et al. (1990) had to assume that the IMF was strongly peaked around 4 $M_\odot$. In other words, they invoked a stellar IMF that contained only stars that evolved to white dwarfs.

Whether white dwarfs are more attractive than the brown-dwarf or black-hole option is partly a matter of taste. It is worth noting, however, that the model of Ryu et al. (1990) suffers from other drawbacks. Smecker and Wyse (1991) studied additional constraints based on the occurrence of Type Ia supernovae. In a halo dominated by white dwarfs, mergers of such objects in binaries would produce Type Ia explosions as well as the associated helium and metals. Smecker and Wyse (1991) concluded that if white dwarfs constitute the halo DM, their precursors must have formed with a much lower binary fraction than is typical. Again, one could argue that since the required star formation is already atypical, this need not be an added worry. Admirers of simplicity, on the other hand, probably regard these results as another nail in the coffin of white-dwarf dark halos.

Theoretical ideas on the mass spectrum of the first generation of stars are not very enlightening. Carr (1990) has pointed out that there are highly plausible reasons to suppose that the first stars were very massive, leading to black-hole remnants, and equally compelling arguments that the first generation of objects might have been substellar brown dwarfs. Other ideas also seem to produce more confusion than clarity. For instance, it has sometimes been argued that the minimum stellar-fragmentation mass and the minimum mass for hydrogen burning are set by different physical processes, so that it is unlikely that the two scales are the same. Since stars are observed to have a mass spectrum that reaches down to the hydrogen-burning limit, the inference is that brown dwarfs must exist. Direct calculations of the minimum fragmentation mass give values around 0.004 $M_\odot$ (Palla et al. 1983), thereby supporting this assertion. However, this argument is countered by the claim that star formation is an accretion process that is only halted when protostellar winds turn on. Since such winds require deuterium burning to have commenced, this suggests only *visible* stars form. The counter-counterargument is that the first stars that form in a protogalaxy will heat the gas and prevent accretion onto other protostellar cores, thereby ensuring that most gas forms brown dwarfs. From this one concludes that there is a lot to learn about star formation.

Lacey and Ostriker (1985) took a more empirical approach and suggested that the "puffing up" of the Galactic disk might be due to black holes with masses around 10^6 $M_\odot$ in the Milky Way halo. This could explain the increase in the stellar velocity dispersion with age, as well as the ratios of the radial, azimuthal, and vertical velocity dispersions. In fact, this places an upper mass of around $10^{6.3}$ $M_\odot$ on black holes (or any other population of dark objects), since higher masses would overheat the disk.

The Lacey and Ostriker (1985) scenario suffers from a couple of drawbacks. Firstly, there is a tendency for such massive black holes to get dragged into the Galactic nucleus through the effects of dynamical friction. Second, as such objects cross the Milky Way disk, they accrete gas from the interstellar medium, leading to excessive X-ray emission. These considerations led Carr and Lacey (1987) to suggest that dark *clusters* with masses around 10^6 $M_\odot$ might be more promising candidates. Such objects get disrupted before causing a major buildup of material in the Galactic center. This disruption requires that the components of the clusters have masses less than about 10 $M_\odot$, which favors brown dwarfs, although black holes are still a possibility. Formation mechanisms for such clusters have been discussed by Carr and Lacey (1987) and Ashman (1990b).

Rix (1992) has used the disk-heating argument to rule out black holes and dark clusters at somewhat lower masses. By considering the heating effects of such objects on the dwarf-irregular galaxy DDO 154, he finds that dark constituents must satisfy $M < 10^5$ $M_\odot$. Limits from the Draco dwarf spheroidal imply an even tighter constraint of $M < 10^4$ $M_\odot$.

The black-hole option has recently undergone an intriguing revival. Gnedin and Ostriker (1992) have suggested that the DM in halos is made up of the black-hole remnants of supermassive objects (SMOs). The novel twist is that the SMOs, which are assumed to form pregalactically, produce considerable amounts of radiation in the young Universe (see also Carr et al. 1984). This radiation alters the abundances of the light elements that are used to constrain the baryonic density of the Universe. Thus primordial nucleosynthesis calculations are not being compared to the true primordial abundances of these elements. The consequence is that Ω_b is higher than the usual limits mentioned above. Eventually, the black-hole remnants cluster to form galactic halos.

Evidence of brown dwarfs in the Milky Way halo comes from observations of globular clusters. Some studies of the stellar-mass function within these objects have revealed evidence for a steepening at low masses (Richer and Fahlman 1986, 1992). This implies that globular clusters have a higher fraction of low-mass stars than other stellar systems and raises the possibility that they might contain significant numbers of brown dwarfs. Richer and Fahlman (1989) carried out star counts in the globular cluster M71. They concluded that between 50% and 90% of the cluster mass was in stars fainter than their limiting magnitude. While stellar remnants might constitute the unobserved objects, Richer and Fahlman (1989) found that stars with masses below 0.33 $M_{\odot}$ were more likely candidates.

Fahlman et al. (1989) and Richer et al. (1990) continued this work and extended the mass function down to about 0.2 $M_{\odot}$ in M13, M71, and NGC 6397. These results supported the earlier claim that the mass function steepens below about 0.4 $M_{\odot}$. Interestingly, Richer et al. (1990) found that M13 had the steepest mass function at low luminosities and thus the largest fraction of low-mass stars. M13 also appears to have undergone less dynamical evolution that the other two globular clusters (see also Richer et al. 1991). Such evolution is expected to produce mass segregation through energy equipartition. This process causes lower-mass stars to migrate to the outer regions of the cluster, or possibly to be lost from the cluster altogether. These observations are consistent with the idea that globular clusters initially contained a large number of low-mass stars and brown dwarfs which have since been lost. Richer et al. (1990) speculate that brown dwarfs lost from globular clusters might explain the halo DM. More recent work on M13 has suggested that around 50% of the mass of M31 may be presently in the form of low-mass stars and brown dwarfs (Leonard et al. 1992).

The idea that the stellar-mass function in globular clusters is steep at the low-mass end has received some support from theoretical studies. *N*-body simulations of the evolution of globular clusters in the Milky Way suggest that steep stellar-mass functions may be required for the clusters to survive to the present epoch (Chernoff and Weinberg 1990). Putting more mass into low-mass stars reduces the total amount of mass loss from the cluster due to stellar evolution, thereby keeping the cluster bound. This is a double-edged sword for proponents of brown dwarfs in the Milky Way halo, since the clusters that are likely to be destroyed and provide the mass of a smooth halo have shallower mass functions and fewer brown dwarfs. Even so, if brown dwarfs are initially present in significant numbers in globular clusters, it seems inevitable that dynamical evolution will lead to many of these objects ending up in the halo.

Other evidence for cosmologically significant numbers of brown dwarfs is provided by cluster-cooling flows. X-ray observations of many clusters of galaxies suggest that large amounts of gas are flowing onto a central galaxy (Fabian et al. 1984; Fabian 1990). If this gas is forming stars, then the colors and luminosities of the accreting galaxies suggest that most of the gas is forming dark objects. The only candidates appear to be very low-mass stars or brown dwarfs. Some support for this interpretation is provided by observations of a cooling-flow galaxy that has a massive near-infrared envelope. Johnstone and Fabian (1989) claim this is consistent with a population of low-mass stars formed from the accreting gas. Ashman and Carr (1988, 1991) and Thomas and Fabian (1990) have suggested that similar quasistatic gas flows may produce galactic halos of brown dwarfs at earlier epochs.

Galaxy clusters also provide more general evidence in favor of baryonic DM, since there is evidence that the DM distribution in these objects is centrally concentrated. This is usually regarded as being indicative of dissipation. In particular, Eyles et al. (1991) have found a centrally peaked DM distribution in the Perseus cluster through X-ray observations. Gravitational lensing of background galaxies also indicate DM distributions that are more concentrated than galaxy distribution in some clusters (Lynds and Petrosian 1988; Tyson 1992).

Despite this circumstantial evidence, attempts to detect brown dwarfs in the halo of the Milky Way have failed so far. Notably, searches for brown dwarfs in the *IRAS* data base have revealed no firm candidates. This does not provide a stringent constraint, although it does illustrate that if brown dwarfs do constitute the halo DM they are extremely elusive.

10.3 Gravitational Lensing

The gravitational-lensing effects of galaxies were discussed decades ago by Zwicky (1937). More recently, both gravitational lensing and microlensing events have started to reveal hints of an enormous potential for DM studies.

Subramanian and Chitre (1987) pointed out that images of gravitationally lensed quasars can be used to constrain the clumpiness within the lensing object. A clumpy-mass distribution tends to amplify the optical continuum of the quasar more than the emission lines, since microlensing due to the clumps is more pronounced for the smaller continuum region. Subramanian and Chitre (1987) applied this idea to MG 2016+112, a quasar that is lensed by an intervening galaxy. The degree of lensing suggests the galaxy has a dark halo. These authors find that the material in the halo is clumped on scales between 3×10^4 and 3×10^7 $M_{\odot}$. This tentative result is consistent with supermassive black holes or the dark clusters of the scenario proposed by Carr and Lacey (1987).

A different approach was adopted by Nottale (1986) who suggested that the flaring of 0846+51W1 could be attributed to microlensing by a brown dwarf in an intervening galaxy halo. This object looks like a quasar in its normal state, but when bright it developed the spectral characteristics of a BL Lacertae object. Notalle (1986) suggested that microlensing would preferentially amplify the blue central region of the object, thereby swamping the characteristic quasar emission lines. The spectrum would then more closely resemble a BL Lac.

Irwin et al. (1989) reported a probable microlensing event in the gravitationally lensed quasar system 2237 +0305. This object was studied by Corrigan et al. (1991), who presented light curves in a range of optical wavebands. Subsequent investigations of these light curves by Webster et al. (1991) suggested that the microlensing object might have a mass as low as 5×10^{-5} $M_\odot$, although ambiguities in interpreting the data make this a tentative result.

These findings are interesting, but more direct attempts to detect baryonic DM using microlensing have commenced recently. Paczyński (1986), amongst others, emphasized the potential of this phenomenon for investigating the nature of DM. There are currently three groups who are in the early stages of conducting microlensing experiments to detect principally brown dwarfs and possibly black holes in the Milky Way halo. Both experiments exploit the fact that massive compact halo objects (MACHOs), such as brown dwarfs or black holes, will cause gravitational microlensing if they pass in front of distant stars. The Livermore–Berkeley–Stromlo experiment is concentrating on fields in the Magellanic Clouds which provide a high density of stars (Bennet et al. 1991). The French microlensing experiment relies on Schmidt plates taken at ESO and uses similar fields (Milsztajn 1991; Ferlet et al. 1990).

A third experiment has recently started collecting data at Las Campanas Observatory (Mateo et al. 1992b). This study uses the Galactic bulge as the background stellar field and can potentially detect lensing objects in the Galactic disk and halo.

Details of the detectability of MACHOs are given by these authors and by Griest (1991) and Griest et al. (1991). Objects in the mass range between about 3×10^{-8} and 200 $M_\odot$ are expected to produce observable signatures, although Gould (1992) suggests this could be extended up to 10^6 $M_\odot$. This is of particular importance since such a range would enclose the entire allowed mass range for compact baryonic objects. Thus, these experiments have the potential for either detecting the DM in the Milky Way halo, or definitively ruling out baryonic DM as the halo material.

11. THEORETICAL IMPLICATIONS

In the above sections some theoretical implications have been sprinkled in amongst the observations. The connection between DM and many cosmological problems is beyond the scope of the present article. (For a discussion of these issues, see papers in the proceedings edited by Barrow et al. 1991.) However, there are a few issues which directly link DM with galactic properties and which are briefly discussed here. The most revolutionary of these, which would invalidate most of the conclusions that have been reached so far in this review, is that there is no DM at all around galaxies.

11.1 Non-Newtonian Gravity

By now it will have become apparent that most of the evidence for DM around galaxies is based on the assumption that the dominant force in these systems is Newtonian gravity. If the virial theorem is inapplicable on galactic scales, much of the evidence for DM would therefore be eliminated. One possibility is that Newtonian gravity breaks down at the low-acceleration characteristic of galaxies.

Milgrom (1983) investigated such an idea and introduced his theory of modified Newtonian dynamics (MOND). In this picture, the usual Newtonian gravitational acceleration g_N is replaced by $\mu(x)g$, where g is the observed gravitational acceleration and $x\equiv g/a_0$. For $x\gg1$, $\mu\approx1$ and the usual Newtonian law applies. However, when $x\ll1$, $g\approx g_Na_0=(GMa_0r^{-2})^{1/2}$. Thus the constant a_0 sets the acceleration at which MOND differs significantly from the Newtonian limit.

The asymptotic-rotation velocity predicted by MOND in the non-Newtonian limit is

$$v_\infty^2=(GMa_0)^{1/2}. \qquad (11.1)$$

Here M is the total mass of the system, so that at low accelerations, MOND always predicts flat rotation curves. Thus the dynamics of spiral galaxies are understood in this theory as a natural consequence of the low-acceleration limit and there is no need for DM. Detailed comparison of MOND predictions with observed rotation curves of spirals have produced good agreement (e.g., Begeman et al. 1991).

Lake and Skillman (1989) and Lake (1989) compared the predictions of MOND with observations of dwarf galaxies. They found that such galaxies put an upper limit on the parameter a_0 that was significantly smaller than the value advanced by Milgrom (1988) to explain the rotation curves of ordinary spirals. The inability of MOND to explain the rotation curves of dwarf and ordinary disk galaxies with the same value of a_0 would rule out the theory. However, Milgrom (1991) has suggested that observational errors in the distance and inclination of the dwarf galaxies are sufficiently large that MOND is still viable. The magnitude of the errors required by Milgrom (1991) seems a little extreme. Moreover, recent observations of dwarfs have produced at least one rotation curve that appears to be completely irreconcilable with the value a_0 required for normal galaxies (Smith and Lake 1992).

It is worth noting that the decline in some rotation curves at large radii (see Sec. 6.4 above), which has been interpreted as indicating the edge of the dark halo, are incompatible with MOND which always produces flat-rotation curves at large radii. As pointed out by van der Kruit (1992), the spirals NGC 891 and NGC 7418 have very different light profiles, but similar rotation curves. This is difficult to understand in the context of MOND, since in the absence of dark halos rotation curves reflect the visible-mass distribution. It is conceivable, but unlikely, that a large gas masses in these galaxies could rescue MOND.

11.2 Galaxy Formation and Baryonic Halos

Many of the results explored in the previous sections have major implications for the process of galaxy formation. As mentioned in Sec. 10, if the Universe is dominated by nonbaryonic material, then pure hot DM models dictate that clusters form before galaxies, whereas cold DM and seeded hot DM leads to galaxies forming hierarchically from smaller subunits. However, there is also an important link between astrophysical processes during galaxy formation and the nature of the DM.

A general picture of galaxy formation has developed in which gas collapses within a preexisting dark halo and eventually forms stars. Gas will dissipate only if it can cool within the age of the Universe, and the gas-cooling time turns out to be a function of halo mass (Rees and Ostriker 1977; Silk 1977; Binney 1977). It has been shown that this scenario explains the observed mass range of galaxies and accounts for the angular momentum of spiral disks (White and Rees 1978; Fall and Efstathiou 1980; Blumenthal et al. 1984). However, in the context of this picture, the increase of the DM fraction with decreasing luminosity of disk galaxies is, at first sight, a surprise.

If the Universe is dominated by nonbaryonic material, then the initial ratio of gas mass to halo mass in protogalaxies just reflects the ratio of baryonic to nonbaryonic matter. In this case, the dark-to-luminous mass ratio in spiral galaxies should be a constant given by this universal value. The fact that it is not leaves two possibilities. The first option is that protogalactic gas is prevented from cooling within low-mass halos, perhaps because it is ejected from the protogalaxy by supernova explosions (Dekel and Silk 1986). Alternatively, some protogalactic gas could form baryonic DM, the effect being largest in the least massive halos (Ashman 1990a).

Some support for baryonic dark halos was provided by the evidence that cooling flows in clusters of galaxies may form significant amounts of baryonic DM in the form of brown dwarfs (Fabian et al. 1984 and Sec. 10 above). The gas in these flows is at high pressure and is cooling quasistatically. Ashman and Carr (1988) showed that similar quasistatic flows can occur at pregalactic and protogalactic epochs. However, in order for a cosmologically interesting density of baryons to cool quasistatically, gas must be reheated until massive galaxies form (Thomas and Fabian 1990; White 1990; Ashman and Carr 1991). In the absence of reheating, most gas in the Universe cools rapidly on subgalactic scales.

An alternative to producing baryonic DM in quasistatic flows is to assume that this rapid-cooling regime is more suitable for baryonic DM formation (Ashman 1990a). This scheme has certain advantages such as forming dark halos before spiral disks, thereby explaining the angular momentum of such disks even in purely baryonic models. It has also been shown that the increase in the dark-to-luminous mass ratio of spirals described in Sec. 6.2 arises naturally in this scenario (Ashman 1990a).

11.3 The Hubble Sequence

In Sec. 6.5, the relation between spiral structure and the DM fraction in disk galaxies was discussed. It appears that early-type galaxies have more centrally concentrated halos, whereas late-type, low-luminosity disk galaxies have such dominant halos that spiral structure is unable to form. These results give some support to the notion that the properties of dark halos have a significant effect on the type of galaxy that eventually forms.

A related suggestion is that barred spirals can only form within fairly insubstantial halos. As noted in Sec. 9, massive spherical halos suppress bar instabilities. While other mechanisms can suppress bars, it seems that bars form more easily if the disk-to-halo mass ratio inside the optical radius is large. A detailed review of ideas relating to galaxy formation and the Hubble sequence is provided by Silk and Wyse (1992).

12. CONCLUSIONS

The evidence that at least some galaxies are dominated by dark-matter halos is overwhelming. Attempts to overcome this conclusion by modifying the law of gravity or invoking other processes have failed. Whether all morphological types of galaxy contain DM is not so clear cut, but the majority opinion supports such a view.

Research in this field seems to be entering a second phase. More critical methods are being employed and many of the simplifying assumptions of the past are being replaced. Theoretical work on maximizing the information that we can obtain from observations that probe DM in galaxies is progressing. Rather than simply establishing whether a particular galaxy has a DM halo, techniques to uncover the extent and shape of halos are becoming more reliable.

While the presence of DM is clear, its nature remains elusive. However, unlike the DM itself, the prospects for uncovering its nature are bright. Microlensing experiments may either detect or exclude baryonic DM in the next few years. Many nonbaryonic candidates have already been ruled out, although the remaining parameter space is going to prove difficult to probe. Some observations and theoretical considerations point towards baryonic DM in galaxies, but are not conclusive. It is also quite possible that the DM in galactic halos is a mixture of both baryonic and nonbaryonic material. Whatever the solution to this problem, we appear to have the tools and the motivation to find it.

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