DARK MATTER IN SINGLE AND DOUBLE GALAXIES

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ABSTRACT. Analyses of rotation curves of spiral galaxies show that the amount of dark matter in a galaxy can exceed the amount of luminous matter by a factor of 4. Lenticular galaxies also appear to have dark halos, but conflicting results have been obtained for ellipticals. Data for double spiral galaxies confirm the results from rotation curves and suggest that the dark halos do not extend much beyond 5 optical radii R_{25}.

1. INTRODUCTION

This review is limited to a discussion of the amount of dark matter in and around galaxies. Dwarf galaxies are not considered. Properties of dark halos of spiral galaxies are discussed in more detail in the review by E. Athanassoula in this volume. The reader is referred to the proceedings of IAU Symposium 117, *Dark Matter in the Universe*, Eds. J. Kormendy and G.R. Knapp (1987), and to van Albada and Sancisi (1986) for more comprehensive discussions of recent progress on dark matter in galaxies.

2. SPIRAL GALAXIES

There now exists indisputable evidence that spiral galaxies are surrounded by dark halos. This can be inferred from a comparison of the distribution of light and the rotation curve: rotation curves indicate the presence of mass in regions where there is no light. The only alternative is that Newton's laws are invalid in the low-acceleration limit (Milgrom 1983, Milgrom and Bekenstein 1987, Sanders 1986). The total amount of dark matter detected so far in spiral galaxies is rather modest from the cosmological point of view. Total M/L_{B} ratios of individual galaxies in blue light may approach 20 $M_{\odot}/L_{\mathrm{B}\odot}$, but the corresponding mass density is still only a few hundredths of the mass density needed to close the Universe.

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Region inside the optical radius

High quality rotation curves are available for several tens of galaxies from the work of Rubin et al. (1985). These rotation curves are based on measurements of the motion of ionized gas. In general they cover the region out to about 0.8 R_{25}. CCD photometry for these galaxies has been obtained by Kent (1986). Adopting a mass-to-light ratio that is constant with radius, Kent finds that rotation curves calculated from the light profiles are in good agreement with the observed rotation curves out to about 0.7 R_{25} in nearly all cases, even though the observed curves are often flat in that region. Beyond 0.7 R_{25} the predicted circular velocity tends to fall below the observed one. Kent's results confirm earlier findings of Kalnajs (1983). The M/L values found are about 1 to 5 (in the red) and can be explained by a typical stellar mix. Thus, inside about two thirds of the optical radius there is no evidence for dark matter.

Region outside the optical radius

To determine the mass distribution outside R_{25} one must rely on the presence of neutral hydrogen (HI). In most spiral galaxies HI is present beyond R_{25}, and in a small number of galaxies the HI disk extends to 2 or 3 times R_{25}. The general flatness of these HI rotation curves implies $M(r) \propto r$ outside R_{25}, while the luminosity enclosed by radius r, $L(r)$, converges to a constant value around $r \simeq R_{25}$.

Two examples from Begeman (1987) are shown in Figure 1. Circular velocities calculated from the luminosity profile by assuming an appropriate constant value of the M/L ratio for bulge and disk are also shown. The M/L ratios have been chosen such as to maximize the contribution by the luminous disk to the observed rotation curve (the 'maximum-disk' case). This yields a lower limit for the amount of dark matter in the system. For NGC 2841 there is about 3.8 times as much dark matter as luminous matter inside the HI radius; for NGC 5033 $M_{\mathrm{dark}}/M_{\mathrm{lum}}$ is about 1.7. In this estimate the amount of neutral hydrogen gas, with a correction for helium, has been included with the luminous matter. Values of $M_{\mathrm{dark}}/M_{\mathrm{lum}}$ in excess of 3 have been found for several other galaxies with extended HI disks.

Note that the rotation curves for NGC 2841 and 5033 are not as flat as those for galaxies with exponential light profiles (see NGC 2403, 3198 and 6503 in Sancisi and van Albada 1987). In NGC 2841 the circular velocity decreases by about 35 km/s beyond the turnover radius of the disk rotation curve. In NGC 5033 the decrease in rotation velocity at 22 kpc occurs close to the truncation radius of the light profile. For both galaxies the decrease can be nicely modelled with the combination of a maximum disk and a halo, but not with a less massive disk.

The disk-halo conspiracy

The results discussed above suggest that luminous material dominates in the inner region and determines the circular velocity inside say 0.7 R_{25}, while the dark halo determines the circular velocity in the outer parts. Apparently luminous matter and dark matter are distributed in such a way that together they produce a more or less constant circular velocity everywhere. This is called the disk-halo conspiracy, or fine tuning of disk and halo (Bahcall and Casertano 1985). It has recently been argued

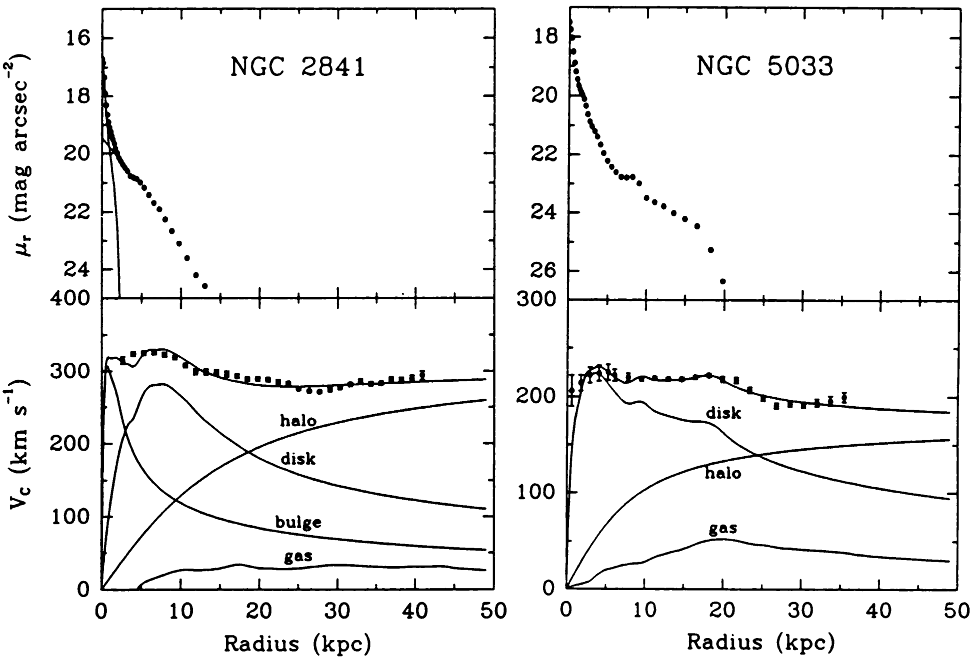

Figure 1. Light profiles and rotation curves for two spiral galaxies with extended HI disks. Upper panels: luminosity profiles (Kent 1986). Lower panels: HI rotation curves (dots with error bars, Begeman 1987) and curves representing the circular velocity of the individual components: stars, gas and halo, and their sum (solid lines).

(Blumenthal et al. 1986, Barnes 1987, Ryden and Gunn 1987) that flat rotation curves and disk-halo coupling arise in a natural way during galaxy formation. In this picture the disk contribution is smaller than the maximum disk however. It is unclear why several luminous galaxies (e.g. UGC 2885) have nearly flat rotation curves inside R_{25} that can be explained by the observed distribution of luminous material only.

3. LENTICULAR GALAXIES

S0 galaxies are sometimes surrounded by rings of stars and gas, which are often more or less perpendicular to the main stellar disk. In some of these polar rings neutral hydrogen has been detected at large radii, and the velocities of the HI clearly indicate the need for a dark halo. The best case is probably NGC 4650A (Whitmore, McElroy and Schweizer 1987; van Gorkom, Schechter and Kristian 1987). Presumably the halo of NGC 4650A is associated with the underlying S0 galaxy and not with the ring. Polar ring galaxies are important probes of the shape of dark halos (Whitmore, McElroy and Schweizer 1987).

Table 1. Mass-to-light ratios of elliptical galaxies.

Probes	Radius	M/L_B (solar units)
Stars	$< 1\,R_e$	10
Ionized gas	$< 1\,R_e$	10
X-ray gas	$< 5\,R_e$	40 ?
Shells	$< 15\,R_e$	100 ??
Companions		
Neutral hydrogen	$< 5 - 10\,R_e$	10 ?

A general search for HI in S0 galaxies has yielded several cases with weak, ring-like HI distributions (van Driel 1987). The spatial orientations of these rings are often rather uncertain and because of this the rings do not always yield reliable circular velocities. Van Driel's results show, on average, an increase in M/L with increasing radius. This is supporting evidence for dark halos around lenticular galaxies.

4. ELLIPTICAL GALAXIES

A number of elliptical galaxies in clusters is surrounded by dark halos according to X-ray measurements, e.g. M87 in the Virgo cluster (Fabricant and Gorenstein 1983). In these cases it is not clear however whether the halo is a component of the galaxy itself or reflects the mass distribution in the cluster. For a proper comparison with spiral galaxies one should consider relatively isolated ellipticals. Although the majority view favors dark halos for ellipticals as well as spirals, the conclusion that ellipticals are surrounded by dark halos is not well founded.

Probes of the gravitational field of elliptical galaxies are listed in Table 1. The quantity R_e in this table is the effective radius, *i.e.* the radius enclosing half the light. The first two probes, stellar velocity dispersions and, in a few cases, rotation curves for ionized gas, cover the region inside the half-light radius. They provide the reference values of $M/L \simeq 10$. Note that this value is somewhat higher than the M/L value for the inner regions of spirals. The other probes go out to about 5 R_e and in case of the shells even to 15 R_e. The X-ray data and shells point to very large M/L's, but two ellipticals with an HI ring give a normal M/L value.

X-ray emission

The main problem with the X-ray data is that the temperatures are uncertain. Because the derived mass is roughly proportional to the temperature, the derived masses are uncertain as well. This has recently been emphasized by Trinchieri, Fabbiano and Canizares (1986). They find that the range in binding masses allowed by the X-ray data does not contradict the M/L values of about 10 found optically.

On the other hand, the X-ray data do not exclude the possibility that ellipticals are surrounded by dark halos.

The interpretaion of the X-ray emission of elliptical galaxies is further complicated by the possibility that a non-negligible fraction of the X-ray emission is due to discrete objects, and not to a hot gas in hydrostatic equilibrium in the galaxy potential. This possibility is especially relevant for low-luminosity ellipticals. In many respects low-luminosity ellipticals are scaled-up versions of bulges of spiral galaxies. This also applies to their X-ray luminosities when compared to the X-ray luminosity of the bulge of M31 (Trinchieri and Fabbiano 1985). In the latter case the X-ray emission is entirely due to discrete sources. Thus the basic premise that the X-ray emission of ellipticals is due to a hot interstellar gas is only partly correct.

Shells

It is now generally accepted that the ripples in the light distribution around several ellipticals (Malin and Carter 1983) are the debris of companion galaxies torn apart by tidal forces. The shells correspond to the turning points in the orbits of the stars in the disrupted companion. Hernquist and Quinn (1987) have modelled the radial distribution of the shells surrounding NGC 3923, which extend to 16 R_e. They assume that the companion has been disrupted completely during one passage of the center of the elliptical. The radial distribution of the shells can then be mapped into a distribution of orbital periods, and this gives the mass distribution. In their model they require a mass-to-light ratio of at least 100 inside 15 R_e. This result is not yet secure because one cannot exclude the possibility that the shells are produced during more than one passage of the center in a shrinking orbit. Dupraz and Combes (1987) have argued that this makes the need for a dark halo quite uncertain.

Neutral hydrogen rings

A few elliptical galaxies are surrounded by rings or disks of neutral hydrogen gas. It appears that these give normal M/L values of about 10. A rather nice case is NGC 5666, studied by Lake, Schommer and van Gorkom (1987). Here the gas extends to at least 10 R_e. Unfortunately the disk is seen under a rather face-on orientation, so the uncertainty in the inclination correction to the rotational velocity is large. Using the axial ratio of the HI distribution gives an inclination of 45°, and the resulting M/L is only about 5. Also for NGC 1052, which has a nearly edge-on, but strongly perturbed ring, the M/L value inside 5 R_e is low ($\sim$ 10, van Gorkom et al. 1986). It agrees with the M/L value found from the stellar velocity dispersion for the central region (Davies and Illingworth 1986). The results for NGC 4278 (Raimond et al. 1981) are more uncertain and would be consistent with normal as well as high M/L.

Companions

In principle the velocities of companion galaxies could provide a useful estimate of the mass of the primary galaxy. The available material is quite meagre however (see e.g Dressler, Schechter and Rose 1986).

From the above discussion it is clear that the information on the presence of dark matter in elliptical galaxies is still inconclusive. The best hope for obtaining more information probably is the measurement of velocities of planetary nebulae in a number of ellipticals (K.C. Freeman, private communication), and more accurate temperature determinations for the X-ray gas. It would also be useful to extend the velocity dispersion measurements to larger radii.

5. BINARY GALAXIES

Studies of single galaxies have not solved the problem of the extent of dark halos. One might hope that observations of binary galaxies would clarify this issue, but this hope has not yet come true, despite considerable effort.

It has long been realized that there are several potential problems with the analysis of binary galaxy velocities. First of all, samples of binary galaxies are contaminated by non-physical pairs. Second, selection effects lead to a non-uniform distribution of viewing angles and orbital phases, which biases the resulting M/L ratio. Third, the orbital ellipticities are unknown. This leads to an uncertainty in M/L of about a factor of two. Turner (1976) considerably improved the methodology to deal with these problems, but his claim of super massive halo's ($M_{\mathrm{dark}}/M_{\mathrm{lum}} \simeq 10$) has not been substantiated by others. For example, Karachentsev (1985) finds no evidence for dark halos. A more subtle problem was recently pointed out by White et al. (1983). They found that pairs in groups have larger velocity differences than more isolated pairs, suggesting that their dynamics is affected by other galaxies. A similar result was found by Picchio and Tanzella-Nitti (1985).

Finally, there is the problem of inaccurate velocities. Typical published mean errors of optical ΔV's are 30 km/s, but from a comparison of different sources for the same object Sharp (1987) finds that the actual errors are closer to 50 km/s. When this is compared with a typical radial velocity difference of 100 km/s it is clear that there is hardly any information on the distribution of relative velocities in these samples. In view of this it is hardly surprising that no correlation between velocity difference and separation has been found in the older studies.

An analysis of spiral pairs with the best data, in particular those of Schweizer (1987) and pairs with 21-cm data (van Moorsel 1987, Oosterloo 1987), which have velocity errors of about 10 to 15 km/s, clearly indicates that dark halos are needed to explain the observations. Typically $M_{\mathrm{dark}}/M_{\mathrm{lum}} \simeq 3$. Furthermore, there is some evidence that the orbital velocities decrease with increasing separation, indicating perhaps that dark halos do not extend beyond about 5 optical radii R_{25}. Unfortunately the number of pure elliptical pairs is too small to solve the question whether elliptical galaxies have dark halos.

An interesting question revealed by the data on spiral pairs is that some of the large velocity differences can only be explained if the halos of individual galaxies are allowed to come into contact. Eventually this must lead to merging of the halos. The merger rate found this way is high: about 20 percent of the pairs should merge within the next few billion years.

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REFERENCES

Bahcall, J.N. and Casertano, S. 1985, *Astrophys. J.*, **293**, L7.

Barnes, J.E. 1987, In: *Nearly Normal Galaxies*, Eighth Santa Cruz Summer Workshop in Astronomy and Astrophysics, Ed. S.M. Faber (New York: Springer), p. 154.

Begeman, K. 1987, *Ph.D. Thesis, Groningen University.*

Blumenthal, G.R., Faber, S.M., Flores, R., and Primack, J.R. 1986, *Astrophys. J.*, **301**, 27.

Davies, R.L. and Illingworth, G.D. 1986, *Astrophys. J.*, **302**, 234.

Dressler, A., Schechter, P.L., and Rose, J.A. 1986, *Astron. J.*, **91**, 1058.

Dupraz, C. and Combes, F. 1987, *preprint.*

Fabricant, D. and Gorenstein, P. 1983, *Astrophys. J.*, **267**, 535.

Hernquist, L. and Quinn, P.J. 1987, *Astrophys. J.*, **312**, 1.

Kalnajs, A.J. 1983, In: *Internal Kinematics of Galaxies, IAU Symp. No. 100*, Ed. E. Athanassoula (Dordrecht: Reidel), p. 87.

Karachentsev, I.D. 1985, *Sov. Astron.*, **29**, 243.

Kent, S.M. 1986, *Astron. J.*, **91**, 1301.

Lake, G., Schommer, R.A., and van Gorkom, J.H. 1987, *Astrophys. J.*, **314**, 57.

Malin, D.F. and Carter, D. 1983, *Astrophys. J.*, **274**, 534.

Milgrom, M. 1983, *Astrophys. J.*, **270**, 365.

Milgrom, M. and Bekenstein, J. 1987, In: *Dark Matter in the Universe, IAU Symp. No. 117*, Eds. J. Kormendy and G.R. Knapp (Dordrecht: Reidel), p. 319.

Oosterloo, T.A. 1987, *Ph.D. Thesis, Groningen University*, in preparation.

Picchio, G. and Tanzella-Nitti, G. 1987, *Astron. Astrophys.*, **142**, 21.

Raimond, E., Faber, S.M., Gallagher, J.S., and Knapp, G.R. 1981, *Astrophys. J.*, **246**, 708.

Rubin, V.C., Burstein, D., Ford, W.K. Jr., and Thonnard, N. 1985, *Astrophys. J.*, **289**, 81.

Ryden, B.S. and Gunn, J.E. 1987, *Astrophys. J.*, **318**, 15.

Sancisi, R. and van Albada, T.S. 1987, In: *Observational Cosmology, IAU Symp. No. 124*, Eds. A. Hewitt, G. Burbidge and Li Zhi Fang (Dordrecht: Reidel), p. 699.

Sanders, R.H. 1986, *Mon. Not. Roy. Astr. Soc.*, **223**, 539.

Sharp, N.A. 1987, *preprint.*

Trinchieri, G. and Fabbiano, G. 1985, *Astrophys. J.*, **296**, 447.

Trinchieri, G., Fabbiano, G., and Canizares, C.R. 1986, *Astrophys. J.*, **310**, 637.

Turner, E.L. 1976, *Astrophys. J.*, **208**, 304.

van Albada, T.S. and Sancisi, R. 1986, *Phil. Trans. Roy. Soc.*, London, **A320**, 447.

van Driel, W. 1987, *Ph.D. Thesis, Groningen University.*

van Gorkom, J.H., Knapp, G.R., Raimond, E., Faber, S.M., and Gallagher, J.S. 1986, *Astron. J.*, **91**, 791.

van Gorkom, J.H., Schechter, P.L., and Kristian, J. 1987, *Astrophys. J.*, **314**, 457.

van Moorsel, G.A. 1987, *Astron. Astrophys.*, **176**, 13.

White, S.D.M., Huchra, J., Latham, D., and Davis, M. 1983, *Mon. Not. Roy. Astr. Soc.*, **203**, 701.

Whitmore, B.C., McElroy, D.B., and Schweizer, F. 1987, *Astrophys. J.*, **314**, 439.