HI ROTATION CURVES OF GALAXIES

R. Sancisi and T. S. van Albada
Kapteyn Astronomical Institute
Groningen University
The Netherlands

ABSTRACT. The observational evidence on the discrepancy between the mass distribution in galaxies derived from HI rotation curves and that derived from the distribution of light is reviewed. In the outer parts the discrepancy is such that in some galaxies there is at least three times as much dark matter as luminous matter. This is a direct consequence of the nearly constant circular velocity far beyond the edge of the visible part of the galaxy, as derived from the motion of HI. The discrepancy is clearly present already near the edge of the visible disk (R_{25}). In the inner regions, i.e. inside approximately 2.5 disk scale-lengths, no dark matter is required, but its presence can not be ruled out. There is no evidence for a dependence on galaxy luminosity or morphological type. These results suggest a strong coupling between luminous matter and dark matter within individual galaxies, and among galaxies as well. Finally attention is drawn to the large-scale asymmetries in the outer parts of galaxies and to possible implications for the vertical distribution of dark matter.

1. INTRODUCTION AND OBSERVATIONAL REQUIREMENTS

The main issue we want to address in this paper is a quantitative determination of the discrepancy between the distribution of luminous matter in galaxies and the distribution of matter derived from the kinematics of the gaseous component. For this purpose neutral hydrogen observations are crucial as they make it possible to trace the kinematical properties of galaxies far beyond the optical disk. In the last decade HI rotation curves have been derived for a large number of systems of various morphological types and luminosities (see e.g. Bosma 1981; Carignan and Freeman 1985). They have been used to calculate total masses and mass distributions, and have revealed significant discrepancies between the luminous and the dynamical mass (see e.g. Faber and Gallagher 1979). The majority of these studies, however, were limited by low angular resolution in the inner parts, poor signal/noise ratio in the outer parts, and occasionally large-scale deviations from axial symmetry.

J. Kormendy and G. R. Knapp (eds.), Dark Matter in the Universe, 67–81.

At present a second generation 21-cm line study for a number of carefully selected objects is in progress. The increased sensitivity of these new observations makes it possible to reach column densities of about 1×10^{19} cm^{-2} for resolutions of ~1 arcmin. The selection criteria are straightforward: the galaxies must have extended, unperturbed HI disks, and be sufficiently inclined to the line of sight - somewhere between 50 and 80 degrees - so that possible effects of warping in the outer parts are small and can be unambiguously corrected for. A wide range of morphological types and luminosities should be covered.

The method generally followed to derive rotation curves from the observed velocity fields is to represent the hydrogen disk by a number of circular rings, each ring being characterized by an inclination angle, a position angle in the plane of the galaxy, and a circular velocity. The orientation parameters, and their variation with radius, are determined from the velocity field. For good cases such as NGC 3198 and 2403 (see below) this can be done with high precision: $\sigma_i \simeq 1^0$ and $\sigma_{pa} \simeq 1^0$. These kinematical inclination and position angles generally agree well with those derived from optical images. The quality of the fit with the derived orientation parameters and rotation curve is assessed by inspecting the residual (model - observed) velocity field. Values of the 'apparent' circular velocity accurate to about 2 or 3 km/s are generally obtained from such fitting procedures. But irregularities and asymmetries in the velocity field often produce larger fluctuations, of order 5 to 10 km/s. A requirement that may be used to obtain an estimate of the true uncertainty in the circular velocity is that rotation curves derived separately for the two sides of a galaxy are symmetrical. For a useful rotation curve the two sides should agree to within 5 - 10 km/s. With the high sensitivity of present HI observations this condition, and not S/N, is the real limitation; it restricts the choice of objects to study. The angular and velocity resolutions which can be obtained with the VLA and Westerbork synthesis radiotelescopes are normally adequate. The rotation curves derived from optical observations (see e.g. Rubin et al 1985 and references therein), which reach out to at most R_{25}, are an essential complement in the central regions where beam smearing effects or HI deficiences can be a severe limitation to the radio observations.

For galaxies viewed edge-on a more sophisticated analysis, using models of the position-velocity maps, is necessary for a precise determination of circular velocities. But, for such large inclinations the possibility of deviations from circular motion and/or HI deficiencies at the line of nodes can never be completely ruled out, and the velocity determination is bound to remain somewhat uncertain. Nevertheless, edge-on galaxies offer a clear advantage for studying also the z-distribution of the gas and of the total mass (e.g. van der Kruit 1981).

2. RESULTS

A number of these newly determined HI rotation curves are shown in Figure 1. They have been reduced to the same linear scale. Morphological types of the galaxies shown vary from early Sb to Sdm; the luminosities cover a range of 260 : 1. Two curves (NGC 2403 and 3198) extend to more than twice the optical size and to many (9 and 11) disk scalelengths. In comparison, UGC 2885, which is well known for its huge dimensions and flat rotation curve (Rubin et al. 1980), does not extend in HI much beyond R_{25} (Roelfsema and Allen 1985), i.e. about 4 disk scalelengths.

All curves remain approximately flat out to the last measured point. They are not, however, entirely featureless. The curve of NGC 4565 shows a slow but steady decline over the outer half of the system. Inside 10 kpc the curve is not well determined; it may be significantly affected by deficiency of gas or by non-circular motions. A drop-off by about 20 km/s is also observed in NGC 5907 beyond the optical edge at about 18 kpc. On one side the gas extends farther out to about 45 kpc, i.e. beyond the symmetrical part (R < 32 kpc) shown in Figure 1. In this tail the line-of-sight velocities appear to drop off towards the systemic velocity in a way similar to that found in the southern tail of NGC 891 (Sancisi and Allen 1979; see also Fig. 10). The asymmetries in these cases are suggestive of non-circular motions. A hint of a decline of V_{cir} beyond R_{25} and a flattening at large radii is also noticeable in NGC 3198. NGC 2403 and UGC 2259 show slightly rising rotation curves.

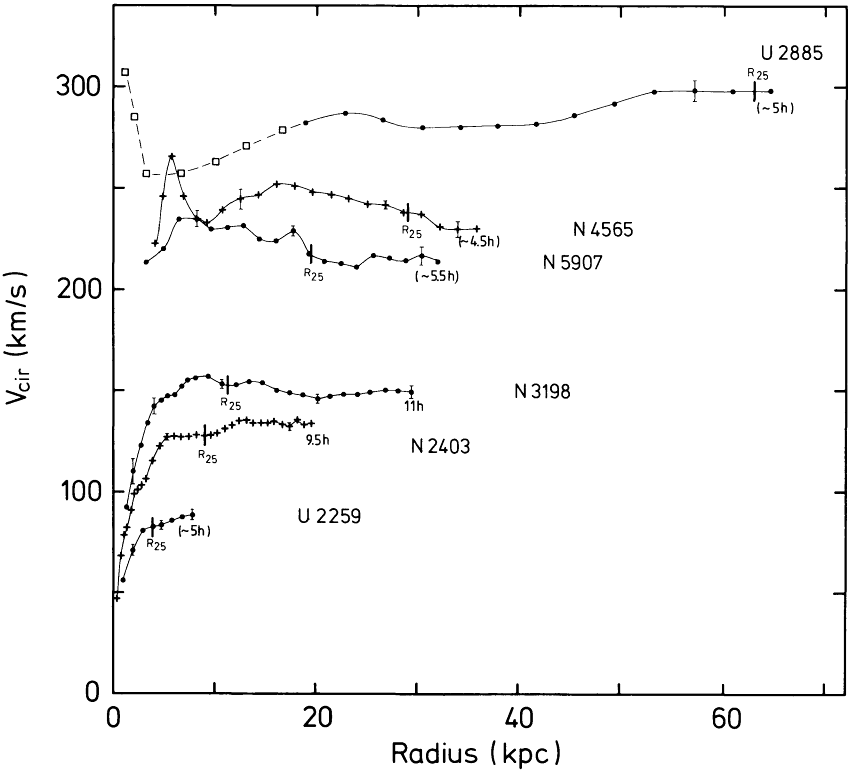

Figure 1. HI rotation curves for a number of spiral galaxies. (Linear scale based on H = 75 km/s/Mpc.) The optical radius, R_{25}, and the number of disk scalelengths, h, at the last measured point are indicated.

Possibly these features are pointing at some significant property of the mass distribution, and perhaps are related to the overall distribution of luminous matter as they occur over the region of the disk or close to its edge. At present we will, however, investigate only the first order flat behaviour of rotation curves, with particular attention to the cases of NGC 3198 and 2403 where the curves remain flat far beyond the optical image. The results for these two galaxies are summarized in Table 1.

Table 1. Parameters for NGC 2403 and 3198.

NGC	2403	3198	
Distance	3.25	9.2	(Mpc)
Disk scalelength, h	2.1	2.7	(kpc)
R_{25}	8.5	11.2	(kpc)
R_{max} (HI)	20	30	(kpc)
R_{max}/h	9.5	11	
V_{max}	135	157	(km/s)
M_{HI}	3.2	4.8	(10^9 $M_\odot$)
M_{total}	7.9	15.4	(10^{10} $M_\odot$)
L_B	0.79	0.86	(10^{10} $L_{B\odot}$)
M_{total}/L_B	10	18	($M_\odot/L_{B\odot}$)
M_{disk} (max)	1.9	4.1	(10^{10} $M_\odot$)
M_{halo} ($R<R_{25}$)	1.3	1.9	(10^{10} $M_\odot$)
M_{disk}/L_B	≤ 2.4	≤ 4.7	($M_\odot/L_{B\odot}$)
M_{dark}/M_{lum} ($R<R_{25}$)	≥ 0.8	≥ 0.5	
M_{dark}/M_{lum} ($R<R_{max}$)	≥ 3.2	≥ 2.7	

NGC 3198. This is clearly the prototype of a spiral satisfying the criteria mentioned in section 1. The HI (Begeman 1985) has been traced out to about 2.7 R_{25}, corresponding to ~ 11 disk scalelengths (Figure 2). The velocity field shows large scale regularity and symmetry. The inclination angle is sufficiently large for a non-ambiguous and precise determination of the circular velocity. The largest correction for changes in inclination in the outer parts is less than 5 km/s. The estimated uncertainties in the rotational velocities in the outer parts are also of the order of 5 km/s and come entirely from the small asymmetry between the two sides of the galaxy. HI circular velocities in the inner region are fully confirmed by recent optical observations (V.C. Rubin 1985, private communication). In Figure 2 (bottom) the observed rotation curve is compared with the model rotation curve calculated from the photometric profile (top) of Wevers (1984), with the assumption of a constant M/L ratio. The value of the latter has been chosen such as to maximize the disk mass while matching the HI rotation curve. It is clear that the observed curve can be accounted for by the visible disk inside about 6 kpc (~ 2.2 scalelengths), but beyond the peak of the model curve the discrepancy between the observed and the expected curves becomes increasingly larger.

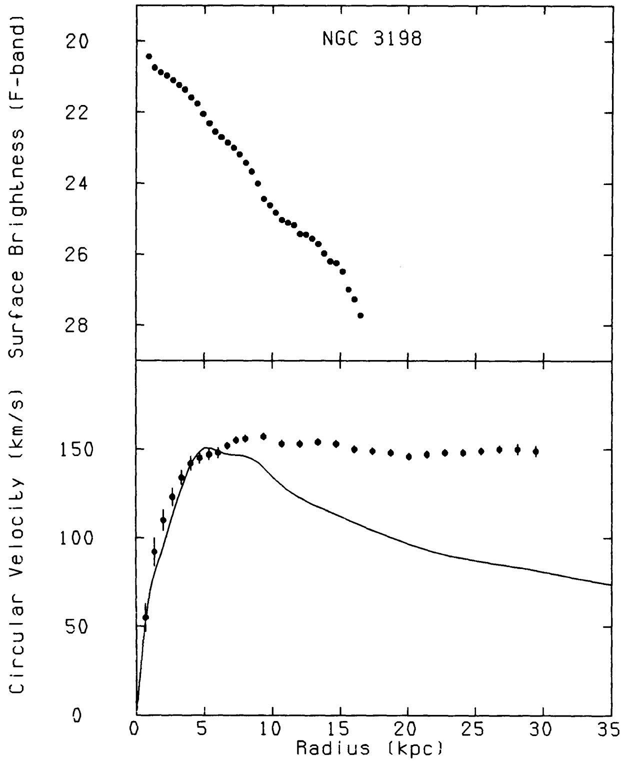

Figure 2. Top: Luminosity profile of NGC 3198 from the photographic surface photometry of Wevers (1984). The scalelength of the disk is 2.7 kpc. Bottom: HI rotation curve (dots with error bars, Begeman 1985), and curve representing the circular velocity of light and gas (solid line). The light contribution has been computed from the luminosity profile by assuming that M/L is constant with radius; maximization of the disk mass while matching the observed rotation curve gives $M/L_B = 4.0$ (stars only). The gas contribution, which includes a correction for helium, is negligible inside 10 kpc.

The conventional explanation for such a discrepancy is the presence of a dark, more or less spherical halo. The amount of dark matter inside the last point of the rotation curve, at 30 kpc, is at least a factor three larger than the amount of luminous matter. The maximum M/L_B ratio for the disk is 4.7 (gas + stars, Table 1), but any lower value, in combination with an appropriate halo, would also be consistent with the HI curve. Such a disk-halo model for NGC 3198 has been discussed in detail by van Albada et al. (1985); see Figs. 3 and 4. The core radius of the distribution of dark matter lies between 1.7 and 12.5 kpc.

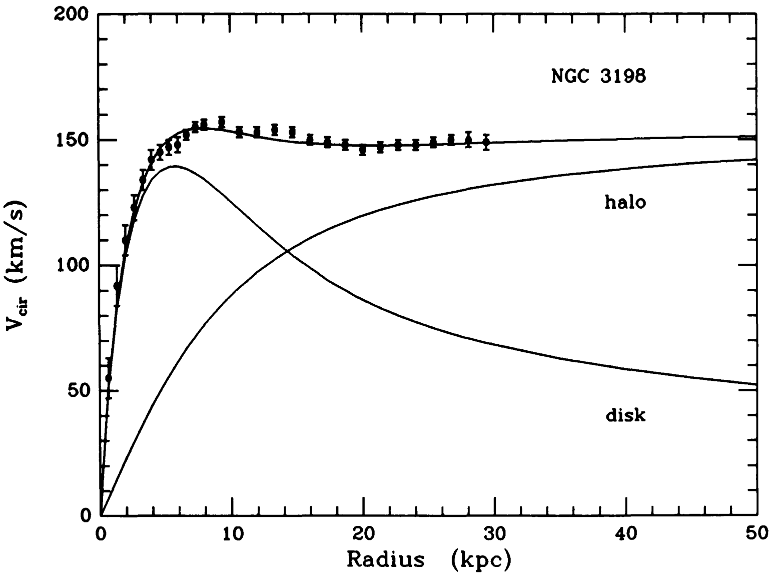

Figure 3. Fit of exponential disk with maximum mass and halo to the observed rotation curve for NGC 3198 (dots with error bars) from van Albada et al. (1985). The scalelength of the disk has been taken equal to that of the light distribution (2.7 kpc). The maximum circular velocity of the disk has been somewhat reduced with respect to that in Fig. 2 to allow a halo with a non hollow core.

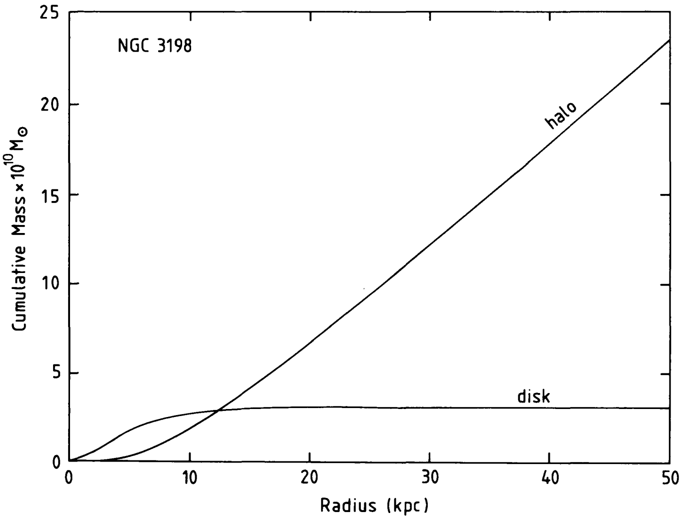

Figure 4. Cumulative distribution of mass with radius for the exponential disk and halo with maximum disk mass shown in Figure 3. (van Albada et al. 1985).

<u>NGC 2403</u>. The rotation curve of this galaxy, showing the symmetry between the two sides, is given in Fig. 5. An analysis of the mass distribution similar to that for NGC 3198 has been made. The luminosity profile (Wevers 1984) has a clear exponential shape (Figure 6 top). A maximum disk fit to the HI rotation curve is shown in Figure 6 (bottom). A large discrepancy between dynamical mass and mass expected from the luminosity profile with - maximum - constant M/L_B shows up at radii larger than ~ 4.5 kpc (≃ 2.2 h). The M/L_B for the disk is very low, less than 2.4. If the gas contribution is also taken into account the M/L_B for the stellar component becomes less than 1.9, suggesting that the true disk mass can not be much smaller than the maximum disk mass (see Larson and Tinsley 1978). The dark mass inside the last measured point at ~ 2.3 R_{25} (= 9.5 h) would then be about 3 times as large as the luminous mass (stars + gas).

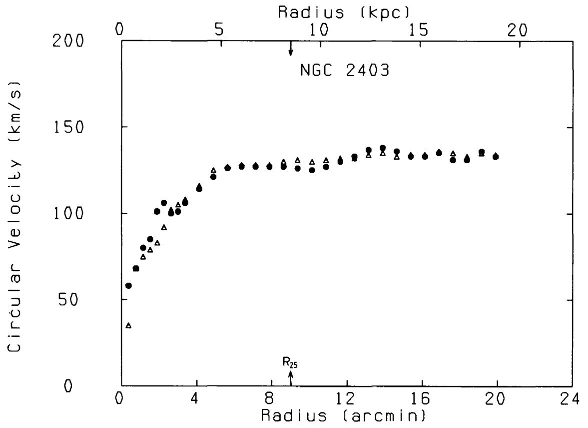

Figure 5.
HI rotation curve of NGC 2403 (Begeman 1985). The receding and approaching sides (triangles and dots) are given separately to show the symmetry of the galaxy.

<u>NGC 4565 and 5907.</u> The rotation curves expected from the photometric profiles (van der Kruit and Searle 1981, Jensen and Thuan 1982) for these nearly edge-on systems (with the assumption of a disk with constant and maximum M/L) show large deviations from the HI rotation curves in Fig. 1. The model for NGC 5907 is shown in Fig. 7; for NGC 4565 see article by Casertano et al. (this volume). Contrary to what has been found for NGC 3198 and 2403 a deviation is present also in the inner parts. For NGC 4565 this may be explained at least partly by the presence of a bulge component. In NGC 5907 the large M/L value of 9 derived for the maximum disk case, which is consistent with the large M/L value of van der Kruit and Searle, may point at the presence of a stellar component not represented in the photometric profile (i.e. hidden by the dust) or at some selective absorption affecting the profile inside 15 kpc. At any rate, the question of the luminosity distribution in nearly edge-on systems ($i \gtrsim 85^{0}$) with a dust layer, should be further investigated before concluding on a real mass discrepancy. In the outer parts the discrepancy between dynamical and luminous mass seems indisputable and similar to that found in the less inclined galaxies discussed above.

The observed 20 km/s drop-off in the rotation curve of NGC 5907 at 18 kpc (≃ 3 h) does not correspond to the drop-off of the curve predicted from the observed light profile and may therefore not be related to the truncation effect studied by Casertano (1983), who based his conclusion on an approximate model for the light distribution with a sharp truncation.

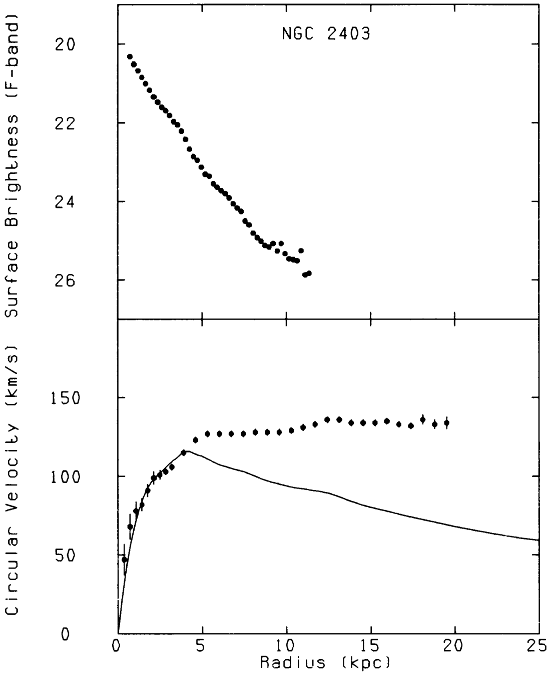

Figure 6. Top: Luminosity profile of NGC 2403 from the photographic surface photometry of Wevers (1984). The scale length of the disk is 2.1 kpc. Bottom: HI rotation curve (dots with error bars, Begeman 1985) and curve representing the circular velocity of light and gas (solid line). The light contribution has been computed from the luminosity profile by assuming that M/L is constant with radius; a value of 1.9 has been used (cf. Figure 2). The contribution of gas to the circular velocity inside 5 kpc is negligible.

Low luminosity galaxies. For dwarf irregular galaxies the observational situation is much less satisfactory than for the higher luminosity systems discussed above. Although rotation always appears to be the dominant form of motion in these systems, the HI distribution and kinematics show large-scale irregularities and asymmetries. The optical picture itself is too irregular to be of use for the definition of the geometrical parameters (inclination angle, line of nodes and center of mass). To our knowledge, it has not been possible to draw any firm conclusion on mass discrepancies and on the amount of dark matter in dwarf irregulars from existing HI observations.

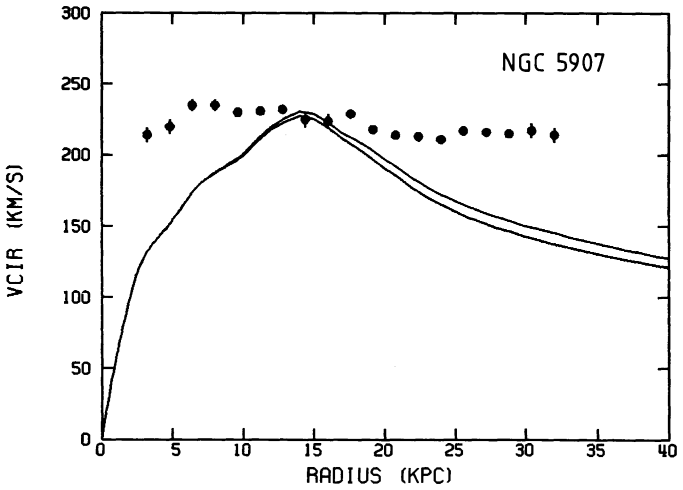

Figure 7. HI rotation curve of NGC 5907 (dots with error bars) and rotation curves (solid lines) representing the distribution of light (lower) and light + gas (upper). The curve for the light has been computed from the light profiles of van der Kruit and Searle (1981) by assuming that M/L is constant and equal to 9 (maximum disk case). Note discrepancy in the inner region between observed and calculated rotation curves (see text).

An interesting and more promising category of objects are galaxies of low luminosity and more regular morphology (type Sd-Sm), and circular velocity between 50 and 100 km/s. The galaxies studied by Carignan and Freeman (1985) fall in this class. Another example, shown in Figure 1, is UGC 2259, which was selected for a 21 cm study by Carignan, Sancisi and van Albada (1985, see also paper in this volume). The HI in this galaxy extends out to about 2.3 R_{25}, has overall regular shape, and its velocity field shows large-scale axial symmetry. The rotation curve rises slowly out to the last measured point. No surface photometry is available yet to allow a detailed analysis such as made for NGC 3198 and 2403. Estimates based on total luminosity and size (R_{25}) indicate the same kind and amount of discrepancy in the outer parts as found in other galaxies. This is consistent with the results obtained by Carignan and Freeman (1985) in three late-type spirals from less detailed HI observations but with complete photometric information.

3. DISCUSSION

a) Conclusions from HI observations.

The main question we have attempted to address is: how large is the mass discrepancy in disk galaxies, and how does it depend on location within a galaxy, on luminosity, and morphological type? According to the conventional hypothesis such mass discrepancy is taken as a measure of the amount of dark matter in the system. From the observations discussed above the following picture emerges (cf. Table 1, see also discussion by Bahcall and Casertano 1985).

1) There is a large discrepancy between dynamical and luminous mass. It begins well inside the optical disk, certainly around 2.5 disk scalelenghts and possibly even closer in, and increases with radius.

2) For the actual ratio of dark-to-luminous matter (M_{dark}/M_{lum}) only certain limits can be set. It could be as low as zero inside 2.2 h, but it is at least as large as 0.5 inside R_{25}. This is based on the maximum disk fit to the rotation curves of NGC 2403 and 3198. The maximum M/L_B values for the disks are between 2 and 5 (somewhat lower if the gas contribution is taken into account). These values seem plausible when compared to the value for the solar neighborhood (Bahcall 1984) and compared to those predicted by stellar evolution models (Larson and Tinsley 1978), and could be close to the true ones.

3) Outside R_{25} non-luminous matter clearly becomes dominant. The ratio M_{dark}/M_{lum} inside the last measured point, out to 20 to 30 kpc ($\sim$ 10 disk scalelengths) can be as large as 3.

4) The ratio M_{dark}/M_{lum} does not seem to vary much with total luminosity. This is indicated by a comparison of low luminosity galaxies (Carignan and Freeman 1985; Carignan, Sancisi and van Albada 1985) with the higher luminosity objects discussed above; see also Bahcall and Casertano (1985). Over a range of one hundred in luminosity the variation may not be more than a factor 2 or 3, with no clear systematic trend.

b) The disk-halo dilemma.

The basic assumption made in the above analysis is that of constant M/L for the disk. The 'halo' is the additional component necessary to explain the rotation curve: the halo mass depends on the assumed value for the disk mass. Examination of two extreme possibilitites - a dominating disk and an insignificant disk - in the two best studied objects NGC 3198 and 2403 (Table 1) may elucidate the question and consequences of the disk-halo ratio.

(i) Dominating disk inside R_{25} (maximum disk, Fig. 8). M_{dark}/M_{lum} would be somewhat less than 1 inside R_{25} with $2 < (M/L)_{disk} < 5$. This would provide a natural explanation for the Tully-Fisher relation, since the maximum observed circular velocity is uniquely related to the amount of luminous matter. However, the conspiracy between disk and halo, required to produce a flat rotation curve, would remain unresolved.

(ii) Insignificant disk, with maximum circular velocity say 0.5 times the maximum observed circular velocity (Fig. 9). In this case $M_{dark}/M_{lum} \simeq 5$ inside R_{25}, and $(M/L)_{disk}$ about 1. There is now no problem of conspiracy of disk and halo as the halo accounts for the flat part of the rotation curve. But a fixed ratio M_{dark}/M_{lum} inside R_{25} is required to explain the Tully-Fisher relation. The large contribution of the presumably 'hot' halo to the total mass inside R_{25} would inhibit the formation of two-armed spiral structure, in contrast to the observed situation for NGC 3198 and 2403. (From the dynamical point of view this is a strong argument against the insignificant disk case.)

There may be an intermediate case between that of the insignificant disk - leading to the rather low values of $(M/L)_{disk}$ and to the other difficulties - and that of a dominating disk - with the puzzle of the disk-halo conspiracy - that minimizes these problems. To some extent however the difficulties will remain. The alternative solution would be that of a disk with M/L increasing with radius and a functional form of M/L(r/h) similar for all galaxies. The z-thickness of such a disk may also increase with radius.

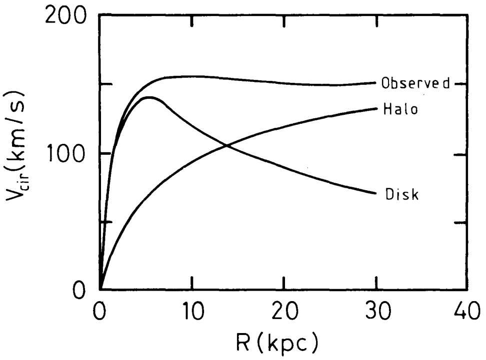

Figure 8.
Diagram showing the decomposition of an observed rotation curve into the separate contributions by disk and halo for the maximum disk case.

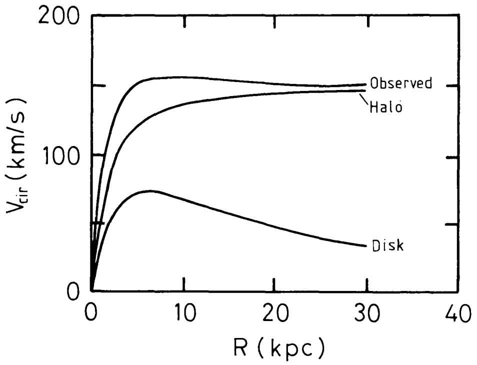

Figure 9.
Same as Figure 8 for an insignificant disk. (M_{disk} = 0.25 x $M_{disk\ max}$)

c) The outer asymmetries.

Above we have emphasized the requirement of axial symmetry for galaxies to derive their rotation curves, and argued that large-scale deviations from symmetry are the real observational limitation. Yet, galaxies do have asymmetries in their HI density distributions and kinematics (cf. e.g. Baldwin, Lynden-Bell and Sancisi 1980). Although the assumption of circular motion may no longer be valid in such cases, the velocity structure may still be used to obtain information on the mass distribution.

Here we present an example of such asymmetries occurring in the outer parts of two edge-on galaxies (NGC 891 and 5907; cf. Fig. 10), which illustrates the limitations in deriving rotation curves at large

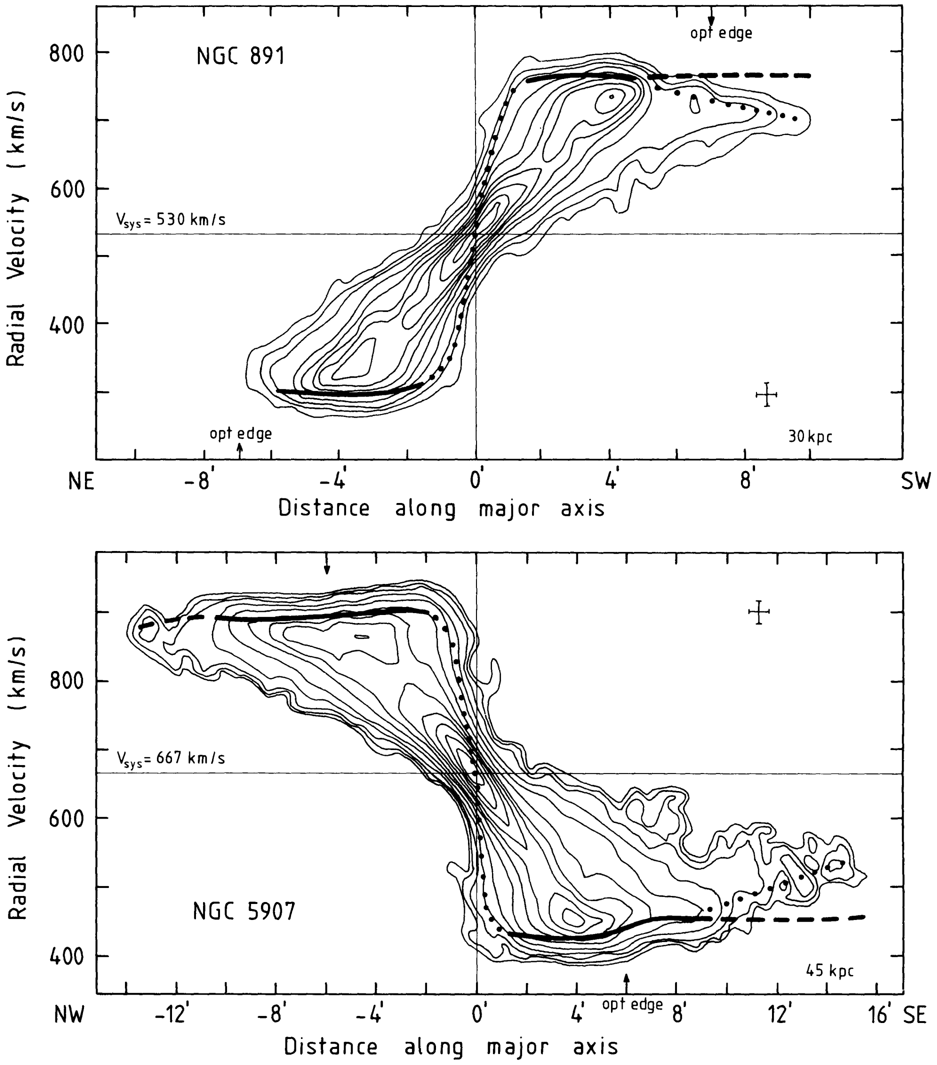

Figure 10. Maps of the edge-on galaxies NGC 891 and 5907 showing the distribution of HI brightness temperature along the major axis, after integration in the perpendicular direction, as a function of heliocentric radial velocity. The contours for NGC 891 are: 0.5,1.6,2.6,5.2 and so on with equal steps of 2.6, for NGC 5907: 0.1,0.3,0.6,1.5,3.0, 6.0, etc. with steps of 3.0 ; units are 10^2 K x arcsec. Crosses indicate angular and velocity resolutions (FWHP). The rotation curves for the symmetrical parts are shown as thick solid lines; in the inner regions (dots) they are rather uncertain. In the tails extending far outside the optical image on the right side of the figure, where the HI radial velocities re-approach the systemic velocities, both the flat extrapolation of the rotation curve (dashed) and the close to Keplerian drop-off (dotted) are shown.

radii and at the same time may provide a clue to the true z-distribution of dark matter. The observations show a picture of an inner system, which is ordered and symmetrical and for which a rotation curve can be derived, changing to an outer disordered and more irregular distribution. In particular: (i) the HI shows a tail on one side, (ii) the velocities in the tail drop back to the systemic velocity and (iii) the HI in the tail remains close (although warped in one of the two objects) to the plane of the disk out to 2 to 3 optical radii. The velocity drop-off, which is close to Keplerian, does not necessarily imply a finite mass distribution. It may also be reconciled with a flat rotation curve in combination with an HI tail displaced from the line of nodes. Or, perhaps, the galaxy is lopsided and the HI moves on eccentric orbits.

Clearly, no firm conclusion can be reached on the mass distribution and on the presence of dark matter in the outermost parts of these systems. But, assuming that dark matter is present, the asymmetrical HI distribution and the location of the tail close to the plane of the disk, may hint at a flattened distribution of dark matter in the outer parts. This is based on the following considerations. The gas in the tail is rotating differentially with relatively short orbital periods of the order of 1×10^9 yrs. If it were part of a primordial, asymmetrical configuration, the survival of the asymmetry would be difficult to explain (cf. Baldwin et al. 1980). If, on the other hand, the gas has been accreted recently and yet has been able to find the plane of the disk at large radii (2 to 3 times optical), this may imply the presence far out of a flat dark system, more or less coplanar with the inner disk.

We thank K. Begeman for the use of his rotation curve data prior to publication and for his assistance with the preparation of figures. We are grateful for the hospitality at The Institute for Advanced Study, where part of this review was prepared, and where we benefited from discussions with S. Casertano, N. Kylafis, and M. Schwarzschild.

REFERENCES

Bahcall, J.N. 1984, Astrophys. J. 287, 926.
Bahcall, J.N., and Casertano, C. 1985, Astrophys. J. 293, L7.
Baldwin, J.E., Lynden-Bell,D., and Sancisi, R. 1980, Mon. Not. R. Astr. Soc. 193, 313.
Begeman, K. 1985, in preparation.
Bosma, A. 1981, Astron. J. 86, 1791.
Carignan, C., and Freeman, K.C. 1985, Astrophys. J. 294, 494.
Carignan, C., Sancisi, R., and van Albada, T.S. 1985, in preparation.
Casertano, S. 1983, Mon. Not. R. Astr. Soc. 203, 735.
Faber, S.M., and Gallagher, J.S. 1979, Ann. Rev. Astron. Astrophys. 17, 135.
Jensen,E.B., and Thuan, T.X. 1982, Astrophys. J. Suppl. 50, 421.
Larson, R.B., and Tinsley, B.M. 1978, Astrophys. J. 219, 46.
Roelfsema, P.R., and Allen, R.J. 1985, Astron. Astrophys. 146, 213.

Rubin, V.C., Ford, W.K.Jr., and Thonnard, N. 1980, Astrophys. J. 238, 471.
Rubin, V.C., Burstein, D., Ford, W.K.Jr., and Thonnard, N. 1985, Astrophys. J. 289, 81.
Sancisi, R., and Allen, R.J. 1979, Astron. Astrophys. 74, 73.
van Albada, T.S., Bahcall, J.N., Begeman, K., and Sancisi, R. 1985, Astrophys. J. 295, 305.
van der Kruit, P.C., and Searle, L. 1981, Astron. Astrophys. 95, 105.
van der Kruit, P.C. 1981, Astron. Astrophys. 99, 298.
Wevers, B.M.H.R. 1984, Ph.D. Thesis, Groningen University.

DISCUSSION

OSTRIKER: When you look at M/L ratios integrated out to an optical radius, you get numbers that are moderate, like M/L ~ 10. But since the light is all in the inner parts, what happens if you work out the local M/L in the outer regions? I.e., if you estimate the added mass and the added light at around the radius of the HI disk, what sort of numbers do you get? Is M/L as big as 1000?

SANCISI: By R_{25} the integrated amounts of light and dark matter are comparable. If you go to greater radii, the local values of M/L become very large, certainly larger than 100.

CARIGNAN: In the case of NGC 3109 (Carignan and Freeman 1985) the local M/L varies from 2 at the center to 10^3 at the last measured velocity point.

PARTRIDGE: Vera Rubin mentioned a couple of cases where you have background quasars shining through the disks of spiral galaxies. Can you get information from these cases about the rotation curve at very large distances, or do asymmetries kill you?

SANCISI: Well, we very much rely on having fully sampled 3-dimensional data to identify large-scale deviations from circular motion, such as asymmetries, warps, etc. Now if you have one point far out, even if it is on the major axis, you don't know what sort of inclination correction to use - the gas could be orbiting in a different plane in the inner and outer parts. So although such an observation provides useful information, such as how far the disk extends, it provides only a very uncertain measure of the rotation velocity.

FABER: You might know more about asymmetries if you had observed more face-on objects. So what are the statistics of the phenomenon? How many galaxies have been observed at very low surface brightnesses?

SANCISI: I would say that the majority of galaxies have lopsided forms. But a real statistical study remains to be done. Warps and asymmetrics occur in the outer parts of galaxies, and only by understanding the physics and state of motion of the gas there can you use it to measure rotation curves. This may in the end prove to be impossible.

I also worry that gas in edge-on galaxies may not lie on the line of nodes. So even if it is on circular orbits, it may not give the rotation velocity. In the well-known case of the galaxy NGC 1961, for example, we know that the gas is not along the major axis.