DYNAMICAL EVIDENCE FOR DARK MATTER IN INDIVIDUAL DISK GALAXIES

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ABSTRACT. We will briefly review the following questions : 1) is there compelling evidence for the existence of dark matter in individual disk galaxies?, 2) where is this dark material?, 3) how much of it is there?, and 4) what is its shape?

1. EVIDENCE FOR DARK MATTER IN DISK GALAXIES

The primary evidence for dark matter in disk galaxies comes from the observed extended rotation curves. Using a now well known procedure, pioneered by Kalnajs (1983), the rotation curve of the visible components, assuming they have a constant mass-to-light ratio, can be computed from the observed radial luminosity profile, and compared to the observed rotation curve. For galaxies with extended rotation curves a discrepancy occurs in the outer parts, where the rotation curve due to the visible components of the galaxy declines. Of course the more extended the rotation curve, the stronger the discrepancy will be. This discrepancy is usually taken to indicate the presence of a dark halo.

From Kent's (1986) work on the galaxies in the sample of Rubin et al. (1985, and refs. therein)., it is clear that in most cases the optical rotation curves do not extend far enough to show the discrepancy clearly (see also Fig. 1). Thus, as has been remarked before by Van Albada and Sancisi (e.g. 1986), the HI-rotation curves of regular galaxies provide the best evidence for dark matter in the outer parts of spirals. If all the matter is in the disk, local mass-to-light ratios of over a 1000 are needed in order to account for the flat rotation curves far out (e.g. Bosma and Van der Kruit 1979).

2. DISK/HALO DECOMPOSITION

Several authors have now published composite disk/halo models of spirals, in order to gain more insight into the properties of the haloes themselves. (e.g. Carignan and Freeman 1985, Van Albada et al. 1985, Bahcall and Casertano 1985, Kent 1986, 1987, Athanassoula et al. 1987;

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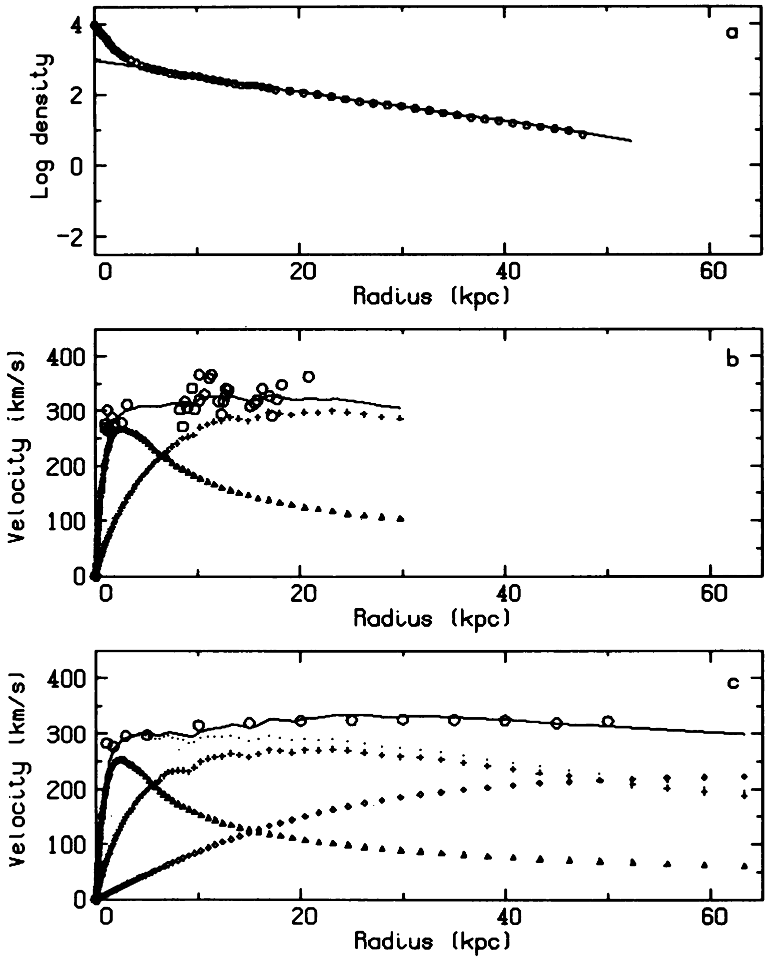

Figure 1. Mass model for NGC 488. a. Radial luminosity profile from Boroson (1981), indicating our bulge/disk decomposition. b. Maximum disk mass model derived for the optical data alone. Note that no halo appears necessary. c. Maximum disk model derived from the HI data. In order to fit the data we now have to add a halo (in this calculation assumed to be isothermal) to the bulge and disk contributions. In both panels b and c the observed data points are represented by open circles, the bulge rotation curve by triangles, the disk by plus signs, their sum by dots, the halo by diamonds, and the total by solid lines.

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hereafter ABP). Since the mass-to-light ratio of the disk is a free parameter, there are various strategies to limit the infinite number of possible models. The main ones are :

a) Best fitting, i.e. least squares fits to the observed curves (Kent 1986, 1987). Even though this is esthetically pleasing, it presupposes an analytical form for the halo, which may not be the correct one.

b) Maximum disk. This solution is generally favored. Note that there are two different solutions under this name :

- i) truely maximum disk : The disk M/L-ratio is taken as high as possible, and no attention is given to the halo part if it existed. The models of Kalnajs (1983) and Kent (1986) are examples of this.
- ii) maximum disk with no hollow halo core : The M/L ratio of the disk is somewhat lower than for a truely maximum disk, so as to allow a 'reasonable' rotation curve for the halo (Van Albada et al. 1985, ABP).

c) Decompositions with spiral structure constraints (ABP). From disk stability theory we know that a sufficient amount of halo may prohibit spiral structure. In fact, the ratio of halo to disk mass determines the multiplicity of the spiral pattern (Toomre 1981). Thus for reasonably bi-symmetric spirals we can delimit the disk mass-to-light ratio between a value below which m=2 structures are prohibited ("no m=2" models), and a value above which m=1 structures (asymmetries) are not suppressed anymore ("no m=1" models).

In practice, for a large number of cases, the requirement for a halo with no hollow core and the requirement that m=1 structures are suppressed give very similar models. Thus in this review we will not distinguish between "no m=1" and "maximum disk without a hollow core halo" models. ABP assessed the "no m=1" models and argued that they appear to be very reasonable decompositions, for a variety of reasons :

- they give good fits to the data.
- they are consistent with the number of arms observed.
- they are consistent with the observed extent of the spiral structure.
- they are consistent with the m=4 components observed in the outer parts of some Sc-galaxies.
- they have reasonable gas fractions.
- they have reasonable mass-to-light ratios, in agreement with other determinations (e.g. those by Van der Kruit and Freeman, 1984, 1986), and with current stellar population models.

One more argument can be added to the above list. For the handful of spirals for which observations of velocity dispersions extend beyond the innermost part, one can calculate, with the help of the mass models, the ratio Q of the radial velocity dispersion to the minimum necessary for axisymmetric stability (Toomre 1964). The value of Q should be above 1, to ensure axisymmetric stability, and not exceed a maximum of order 2.5, above which spiral structure would be stifled (e.g. Athanassoula and Sellwood 1986). For the galaxy NGC 488 the Q values, calculated with the help of dispersion measurements of Illingworth and Kormendy (in prep.) and a rotation curve obtained from data of Peterson (1980) and recent VLA 21-cm line data by one of us (A.B.), are indeed in the requested interval.

Van Albada and Sancisi (1986) and Kent (1986) argued whether 'bumps' on the observed rotation curves require that the maximum disk

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solution should be adopted. We wish to point out here that such an argument should be considered with care. It is only relevant for round, or nearly round lenses, rings or plateaux, or for the mean axisymmetric motion due to other perturbations, while frequently the bumps are observed only on single long-slit position-velocity diagrams, and can be traced back to non-axisymmetric components in the disk (e.g. the crossing of an arm).

Thus the "no m=1" solution seems to do well in all the tests it has been subjected to. On the other hand the "no m=2" solution has gas fractions and disk M/L ratios on the high and the low side respectively (ABP). Furthermore, for the "no m=2" model of NGC 488 (see above), we found uncomfortably high Q values. Some of these objections become less severe if one shortens the distance scale, and could be further eased by appropriate changes in the absorption corrections. Note that then the M/L values derived in this way will not be in agreement any more with those derived by Van der Kruit and Freeman (1984, 1986) from the vertical scales of disks. Changes in the deprojection of the observed dispersions affect the Q values. As things stand now, we favour the "no m=1" solution. The arguments are not precise enough to allow us to assess solutions in between that and the "no m=2" solution.

3. SUMMARY OF HALO PARAMETERS

In ABP we showed that there is a trend between the ratio of halo mass to luminous mass and the integrated color of the galaxy. This had already been discussed by Tinsley (1981) : late type spirals should have comparatively more dark matter within their optical radius than do early type spirals. In view of the interest in this trend, we checked that it does not arise artificially from either our modelling procedures or from the fiducial radius within which the masses are evaluated.

In the ABP sample only a disk, a halo and, whenever present, a bulge component were taken into account for the mass models. The neglect of the gas contribution, as explained in that paper, artificially increases the halo mass, and this effect will be obviously more important for galaxies with a large gas content i.e. primarily late types. This would enhance the above mentioned trend. We have thus reconsidered the question using two smaller, but more homogeneous samples, for which good quality HI data are available. The first one is, to a large extent, a subsample of the ABP one, and has available photometry in the blue band. For the second one we used photometry in the red band from Kent (1987). For both samples we have calculated mass models in which the gas distribution is explicitly taken into account and plotted the ratio of halo to stellar mass as a function of galaxy color. The trend suggested by Tinsley is at least as clear as in the ABP sample. Adding the gas to the stellar mass does not alter this trend significantly.

For both samples we have repeated the exercise calculating the mass ratios within other radii, like the Holmberg radius or a dynamically defined radius (e.g. a multiple of the radius at which the disk rotation curve reaches its maximum) and find that the trend still exists.

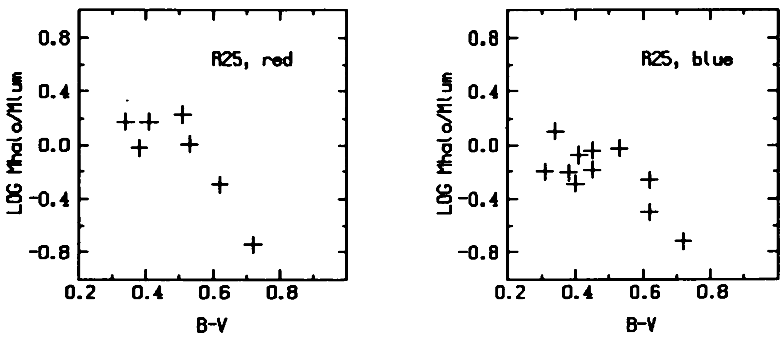

Figure 2. Ratio of halo mass to stellar disk + bulge mass, evaluated at R_{25}, as function of color, for the two samples described in the text.

The relation between the luminous and dark material seems very tight, and in fact has lead to the notion of a 'conspiracy' between the two, in order to give flat, featureless rotation curves (Bahcall and Casertano 1985). There are several ways in which this conspiracy can be expressed (ABP), e.g. by a trend between the central density of the disk and that of the halo, and by the fact that haloes of early type galaxies seem more concentrated than those of late types. The compression of halo material during the formation of the disk may play a crucial role here (cf. Blumenthal et al. 1986).

4. GALAXIES WITH LOW SURFACE BRIGHTNESS DISKS

Although galaxies with low surface brightness disks are not very well represented in the samples usually discussed for rotation curves, they might shed some light on processes which are also important in 'normal' galaxies. In Bosma et al. (1987) new data are presented for the galaxy NGC 5963. This galaxy has a fairly 'standard' rotation curve and gas density profile, similar to those of NGC 2403, 3198 or 6503. Yet its outer disk has low surface brightness (see Romanishin et al. 1982). From their mass modelling Bosma et al. derive a very concentrated halo, with a core radius about twice as small as for Sc galaxies with comparable rotation curves and gas density profiles. The model has two disk components, a gaseous and a stellar one. Assuming that the gas has a constant velocity dispersion of 8 km/s and using a maximum disk model as discussed in sec. 2, we calculated the stellar velocity dispersion necessary for marginal disk stability, as function of radius. We find that this is high in the inner high surface brightness part and only of order 8 km/s in the outer low surface brightness disk, i.e. a value very similar to the gas velocity dispersion. One can thus speculate that the

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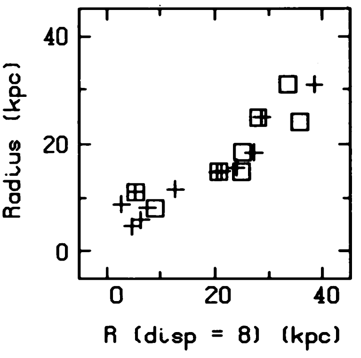
Figure 3. Radius at which the minimum stellar radial velocity dispersion necessary for axisymmetric stability drops below 8 km/s, compared to the optical radius R_{25}



gas disk of this galaxy is and has been almost Jeans stable, whence the absence of star formation and the low surface brightness of the disk.

A similar effect may determine the outer edge of the disk of every galaxy. Using maximum disk models, we have evaluated for galaxies in the two samples mentioned in the preceeding section the radius at which the minimum stellar radial velocity dispersion drops below 8 km/sec. In figure 3 we show the tight relation between this radius and the optical radius. Fall and Efstathiou (1980) have found a similar correlation and have argued that outside this radius the gas is Jeans stable and does not form stars.

5. SHAPE OF THE HALO

Unfortunately dynamical arguments are not tight enough to allow us to determine precisely the shape of the halo, even if we neglect complexities due to non-axisymmetries (see Binney 1986 for arguments about triaxial haloes). We will thus primarily focus the following discussion on whether the halo is more spherical or more disk like.

a) From stability arguments alone one cannot conclude anything about the shape of the dark halo. A spherical halo is indeed well known to stabilize (Ostriker and Peebles, 1973, etc..), but it is wrong to reverse the argument and conclude that the halo has to be spherical in order to stabilize. Athanassoula and Sellwood (1986) have shown that a hot disk by itself can ensure stability, without help from a spherical halo.

b) Binney et al. (1987) argue that for our Galaxy the axial ratio of the halo potential is in between 0.3 and 0.6, provided that the kinematics of the halo material is like that of extreme population II stars, the halo is a perfect spheroid, and the combined disk/halo potential is of a Stackel form. The first hypothesis may well not be valid, particularly if the halo material is non-baryonic. Furthermore modelling procedures may influence the result, as argued by Sommer-Larsen (1987), who showed that round models, provided that they are not constrained to be scale-free, can be fitted to the available data.

c) The polar rings around S0 galaxies may give some evidence on the shape of dark haloes (or for minimalists : only on the shape of the dark haloes around these galaxies). Schweizer et al. (1983) presented data for A0136-0801 and showed that the mismatch between the disk velocities and the polar ring velocities did not exceed 10 - 15 % and therefore argued for an axial ratio of the potential of larger than about 0.9. More recent results by Whitmore et al. (1987) for 3 such galaxies indicate values of 0.86 ± 0.21, 1.05 ± 0.17 and 0.98 ± 0.20. For A0136-0801 the data are good enough to allow a disk/halo decomposition, from which we find that from the disk alone we get an axial ratio of the potential of about 0.7 in the region of interest. The halo around this galaxy has thus to be substantially rounder to produce the agreement between the disk and ring velocities.

d) The warping of the HI-layer has been puzzling theoreticians for some time now, and most favour a solution involving a halo. However, so far their investigations have not provided us with a precise, sharp tool delineating the shape of the halo.

e) The flaring of the HI-layer may provide interesting constraints on the shape of the dark halo. For NGC 891 Van der Kruit (1981) already argued that the observations could be better described by a model with constant disk M/L and a halo, rather than by a model in which all the mass is in the disk and its M/L varies with radius. However, in his models he treated the gas as test particles, and neglected the halo and bulge mass. These two assumptions will artificially increase the flaring in the outer parts of the disk in the disk + halo models, since there the gravity responsible for keeping the gas near the plane is due mainly to the gas itself, while the halo contribution to the vertical force should not be neglected.

These assumptions can be easily relaxed. We thus reran the case of NGC 891, assuming, like Van der Kruit (1981), that both the gas velocity dispersion and the thickness of the stellar disk do not vary with radius. The results no longer show such a clearcut distinction between a "no m=1" model with spherical halo, and an all-disk model. Luckily, for other galaxies the situation is more favourable. For M31 we find that the flaring for a spherical halo model is about that required in the Brinks and Burton (1986) model, which gave a reasonable fit to Brinks's observations.

In order to get a feeling of how much information on the shape of haloes can be obtained from a suitably selected sample of edge-on galaxies, we have run models with parameters taken from those of representative galaxies with more face-on orientations. We have found that the differences between spherical and disk halos can be tale-telling, provided the measurements extend out far enough in radius. An example for a model with the parameters of the well studied galaxy NGC 3198 is shown in Fig. 4. Here we compare, for three different values of the stellar disk thickness, the flaring of the HI disk for maximum disk

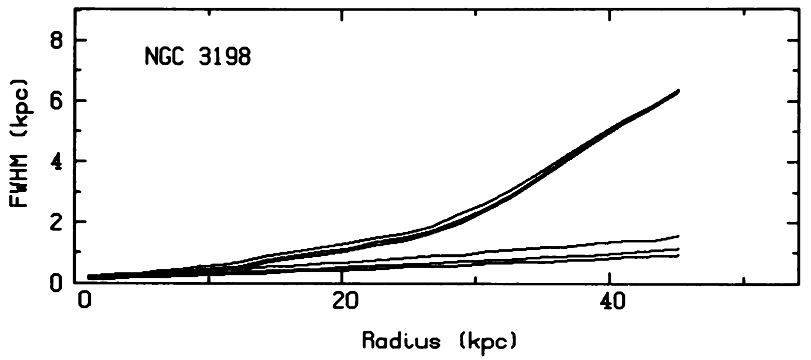


Figure 4. Predicted flaring of the HI disk in NGC 3198 for maximum disk + halo models (upper curves) and for all-disk models (lower curves)

+ halo models (upper three curves), and for all-disk models (lower three curves). The difference between the two sets is very clear and thus observations of this galaxy, or others with similar parameters, should enable us to put stringent constraints on the shape of the halo. Note also the occurrence of a small 'knee' or change of slope around a radius of 28 kpc. We found such features in several cases, and they could always be explained by changes in slope of either the stellar luminosity or the gas density profile. We will address the halo shape problem further with specific observations in the near future.

6. CONCLUSIONS

In conclusion, we think that the evidence for dark matter (barring some suitable form of modified dynamics) is quite strong, and that, using composite disk/halo models and applying dynamical contraints, we have already made a reasonable inroad in unravelling some of the properties of the dark haloes. We need to sharpen our tools on two outstanding questions : the shape, for which we have given some hints, and the extent of the halo.

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