Dark Matter in Disc Galaxies

A. Bosma

Observatoire de Marseille, 2 Place Le Verrier, 13248 Marseille Cedex 4, France

Abstract. Recent work on the mass distribution in spiral galaxies, using mainly HI observations, is reviewed. The principal problem is still to determine to what extent the dark matter is important in the inner parts of a galaxy, or in other words, how dominant is the self-gravitation of the disc. Studies of the shapes of rotation curves show that in detail there is sufficient individuality in spiral galaxies to prohibit the construction of “Universal Rotation Curves”. A detailed account is given of the method of Athanassoula et al. (1987), where swing amplifier criteria are applied to set a range in the mass-to-light ratio of the disc. To restrict this range further, other methods might be useful. For a number of bright spirals the rotation curve drops just outside the optical image, but this feature by itself cannot constrain unambiguously the mass models. The use of velocity dispersions seems a promising way, though the observational problems are hard. Within the uncertainties, discs can be close to “maximum”, even though a range of values cannot be excluded.

1. Introduction

The standard way to construct a mass model for a spiral galaxy is to make composite disc/halo models assuming a “maximum disc” solution, or to adopt a “best fit”. In such models, the data from surface photometry are used, assuming constant mass-to-light ratios, to calculate the expected rotation curve for the visible components, bulge and disc. From the observed HI gas density, and a suitable factor to include helium, a rotation curve is calculated also, and quadratically added to the first one. The resulting curve is then compared with the observed rotation curve, and an additional dark halo component is introduced when necessary.

For extended HI rotation curves, such an analysis has been done by several authors, e.g. Begeman, Broeils & Sanders (1991). The constancy of the mass-to-light with radius within each component is usually justified by the absence of colour gradients. Indeed, data of De Jong (1996) shows that colour gradients are small, and if present, they are in the sense that discs become bluer outwards. In that case the use of near infrared data is preferred, since it accounts better for the contribution to the mass of the old stellar disc. From De Jong’s (1996) data, it follows that the ratio of the blue (B-band) and near infrared (K’-band) scalelengths is about 1.15 for 85% of his sample. However, from Verheijen’s...
studies on the spirals in the Ursa Major cluster (Verheijen 1997), a much larger spread in the ratio of scalelengths is seen (cf. Tully et al. 1996).

The primary trend in these models is that the importance of dark matter increases with decreasing luminosity: small galaxies seem to be more dark matter dominated than large galaxies (cf. Broeils 1992). Another trend is that the rotation curve of the gas component has more or less the same shape as the halo rotation curve: if all matter were is a disc, the ratio of gas mass to total mass becomes constant in the outer parts (cf. Bosma 1978, 1981b; Carignan et al. 1990).

However, such results, based as they are on the assumption of maximum disc, may not be correct. In this review, I will comment on the recent work on rotation curves and mass models of spiral galaxies, and in particular address part of the question whether the maximum disc hypothesis is justified. For another discussion on this last topic, using arguments principally concerning barred galaxies, see Sellwood (this volume).

2. Shapes of rotation curves

There have been many attempts to infer something about the amount of dark matter in spiral galaxies by looking at the shape of the observed rotation curves. Part of this quest is motivated by the desire to arrive at a simple rule of thumb concerning the behaviour of rotation curves as function of Hubble type and luminosity. However, as we shall see, the details in individual galaxies are important at some level, and no such thing as a universal rotation curve exists.

2.1. “Wiggles”

One argument for the maximum disc hypothesis is the presence of “wiggles” in the rotation curves, in particular those derived from long slit spectroscopy. This was already remarked upon by Kent (1986) and Van Albada & Sancisi (1986). These wiggles can, remarkably, be fitted using the maximum disc approach, even though it is quite likely that the “wiggles” in the position - velocity diagram resulting directly from the spectroscopy are due to the crossing of the spiral arms, as in the case of NGC 2998 (cf. Rubin et al. 1978). Freeman (1992) likewise shows a few cases from the work of Buchhorn (1992) using the Mathewson, Ford & Buchhorn (1992) data.

However, when the motions giving rise to the “wiggles” are non-circular motions due to the spiral arms, it is technically incorrect to speak of rotation curves here. Visser (1980), in his study of M81, shows that the average rotation curve of a two-dimensional velocity field strongly perturbed by motions due to the spiral arms is wiggly, while the “true” rotation curve he needs to fit such a velocity field with a model based on density wave streaming motions is smooth and without “wiggles”. Thus the “wiggle” argument is not usable in the context of rotation curves. In any case, Van der Kruit (1995) shows that also for non-maximum discs the wiggles can be fitted.

The only rational way to reformulate the “wiggle” argument, as proposed by Binney (priv. comm.), is to consider that, since they are there and due to spiral arm streaming motions, there should be a non-negligible part of the mass in the disc. A similar argument is made by Sellwood (this volume) concerning
the capability of fitting gas flow models of barred spirals to high resolution two dimensional velocity fields.

2.2. Complete rotation curves

A first requirement to discuss rotation curve shapes is to have them defined over as large a range in radius as possible. This means that HI rotation curves need usually to be supplemented with optical data in the inner parts, to assure a better definition of the curve there. This can be done by e.g. long slit spectra of optical emission lines - usually Hα and [NII] - or, preferably, with two-dimensional Fabry-Pérot data. Alternatively, CO observations in the millimeter wavelength range can be used, either from single dish data, or from interferometry. Sofue (1997) published a number of combined rotation curves using available data in HI, CO and Hα.

Begeman (1989) developed a method to correct HI rotation curves for the effects of beam smoothing, using high sensitivity data for the galaxy NGC 3198. He fits multiple gaussians to the line profiles, and retains the principal peak. His results have been compared with long slit optical emission line data by Bottema (1988) and Hunter et al. (1986), and with Fabry-Pérot data by Corradi et al. (1991). The agreement between all these data is excellent.

The necessity of good data in the inner parts cannot be overstressed, since in particular for the multi-component mass models, the outcome of the decomposition depends on a correct determination of the rotation curve at all radii. This is particularly important for dwarf galaxies, where the disc rotation curve is often compared with observational data consisting of only a couple of data points.

2.3. Conspiracies?

In the late seventies, the emphasis on the rotation curve shapes concerned their flatness: the absence of the expected Keplerian decline of the rotation curve beyond the optical image implied the presence of a large amount of mass with high mass-to-light ratios (Bosma 1978). The systematics of the rotation curves as function of Hubble type and luminosity were determined by Rubin and her collaborators in a series of papers (Rubin et al. 1978, 1980, 1982, 1985).

In the mid-eighties arguments centered on the flat and featureless nature of the curves (Bahcall & Casertano 1985). The question how a thin disc and a presumably round dark halo conspire to keep the rotation curve flat without showing any marked feature was raised, and an answer was found in the process of adiabatic compression of the halo material when the disc was formed (cf. Barnes 1987, Blumenthal et al. 1986).

However, some galaxies have rotation curves which decline just beyond the optical image, and stay more or less flat thereafter. Early examples are NGC 5033 and NGC 5055 (Bosma 1978, 1981a), and also NGC 5908 (Van Moorsel 1982). Thus the notion of featureless rotation curves never corresponded to hard reality. Two more examples, NGC 2683 and NGC 3521, were given by Casertano & Van Gorkom (1991), who speculated that declining curves are linked with discs having short scalelengths. However, Broeils (1992) finds cases of declining curves for galaxies with large disc scalelengths.
In any case, all these examples show that the process of adiabatic compression is not fully operational for all spiral galaxies. In particular, a partial decoupling between disc and halo is seen in a non-negligible fraction of the brighter spirals.

2.4. Universal Rotation Curves?

Persic, Salucci & Stel (1996) propose that the shapes of rotation curves follow a systematic pattern as function of luminosity only. Their conclusions are based on a re-analysis of the data by Mathewson, Ford and Buchhorn (1992), although the notion of universal rotation curve is older (e.g. Rubin et al. 1980). The rotation curves for low luminosity galaxies are rising, those of intermediate luminosity are more or less flat, while those of the highest luminosity galaxies are falling.

However, a cursory inspection of the 12 curves with the highest rotation velocities in the sample of Persic et al. (1996, see also Persic & Salucci 1995 for more details) shows that their weighted average is not declining at all. Moreover, about 18% of the galaxies in their sample have inclinations larger than 85°, and about half of these are seen exactly edge-on. This has consequences for the shape of the resulting average rotation curves: as has been shown by Bosma et al. (1992) and Bosma (1995), the opacity in the inner parts of large spirals tends to make the inner slopes of Hα rotation curves too shallow compared to the true rotation curves. Thus the averaging procedure should be redone without taking the data from highly inclined galaxies into account.

Even so, Verheyen (1997) reexamined the problem of universal curves, and finds that for the 30 rotation curves in his sample of spiral galaxies in the Ursa Major cluster about 10 do not fit at all to the universal rotation curves of Persic et al. (1996). This means that although there is some merit to the scheme, at the 10% - 20% level the notion of universal rotation curves breaks down.

3. Spiral structure constraints

3.1. Swing amplifier criteria

Athanassoula et al. (1987) introduce criteria from spiral structure theory, and in particular those for swing amplification (Toomre 1981), in order to get limits on the dynamical importance of the disc. Since observed discs are usually bisymmetric, it seems natural to ask for the possibility to have amplification of m = 2 structures, which imply a minimum for (M/L)_{disc}. On the other hand, one would like to suppress m = 1 structures, which implies an upper limit for (M/L)_{disc}. This limit usually coincides with the requirement to have “maximum discs” but with halos with non hollow cores. Athanassoula et al. (1987) find that these latter models are preferred when considerations of stellar populations and the buildup of Sc discs at a constant rate of star formation over a Hubble time are taken into account.

The way this works is illustrated in Figures 1 and 2 for the galaxy NGC 3198. For the swing amplifier to work, we need several quantities which depend on the rotation curve. These are the parameters $\Gamma$ and $\chi$, given by:

$$\Gamma = -\frac{R d\Omega}{\frac{d\Omega}{dR}}$$

(1)
where $\Gamma$ is the dimensionless shear rate. This quantity is 1.0 for exactly flat rotation curves, 1.5 for Keplerian curves and 0.5 for a curve rising as the square root of the radius. The other quantity is

$$X = \frac{\kappa^2 R}{2\pi G m \mu} \tag{2}$$

As can be seen, the active disc mass, $\mu$, comes in, as well as the number of arms, $m$. The rotation curve is also represented via the epicyclic frequency, $\kappa$.

Athanassoula (1984) rediscussed the swing mechanism presented by Toomre (1981), and calculated for various values of $\Gamma$ the maximum growth factor of the swing amplification as function of $X$ for 3 typical values of the Toomre parameter $Q$. In Athanassoula et al. (1987) we use an interpolation method to determine the amplification factor for any value of $\Gamma$ and $X$. As a result, we can for a given mass model work out its consequences for the amplification of $m = 1, 2, 3, \ldots$ structures, and calculate graphs such as presented in Figure 2. It can be easily seen from Figure 2 that if we lower the mass-to-light ratio of the disc with a factor 2, the curves for $m = 2$ become those in the top panel, and the curves for $m = 4$ those in the middle panel (since $m \mu$ is what matters).

For NGC 3198, it is clear that the “no $m = 2$” criterion leads to a disc rotation curve whose maximum velocity is $105 \text{ km s}^{-1}$. This can be compared to the value of $100 \pm 19 \text{ km s}^{-1}$ derived by Bottema (1993) from his criterion based on his velocity dispersion work, and also by the maximum values of 93 and $100 \text{ km s}^{-1}$ calculated by Navarro (1998) for his models, which are partly based
Figure 2. Curves of $\Gamma$ (dotted line) and $X$ (continuous line), at left, and the maximum amplification for three values of $Q$ ($Q = 1.2$ : dashed line, $Q = 1.5$ : continuous line and $Q = 2.0$ : dotted line), at right, for the “maximum disc” model of NGC 3198 shown in Figure 1. At the top, the results for $m = 1$, in the middle, the results for $m = 2$, and at the bottom, the results for $m = 4$. 
on notions from cosmological simulations, and include tacitly that the adiabatic compression of the halo material due to the disc formation is functioning as predicted. While the Bottema criterion is still in rough agreement with the swing amplifier criteria given the uncertainties, the models of Navarro (1998) are not anymore: for them the disc is just a bit too light to allow swing amplification of $m = 2$ structures.

In conclusion, the method used by Athanassoula et al. (1987) gives a range of values for the mass-to-light ratio of the disc, with the upper limit very often close to or identical with a “maximum disc with no hollow core halo” solution, and a lower limit which is higher than the values current fashionable arguments from cosmological simulations seem to advocate.

3.2. Recent applications of swing amplifier criteria

Vogt et al. (1996) began a campaign to obtain an idea of the rotation curves of faraway galaxies, thanks to powerful equipment like the Hubble Space Telescope and the Keck Telescope. For about a dozen spirals they derive position velocity curves, which are heavily affected by aperture effects, since the slit width is non-negligible compared to the size of the galaxies. For one galaxy, 0305-00115, at $z = 0.48$, Fuchs, Möllenhoff & Heidt (1998) argue on the basis of swing amplifier criteria that a dark halo ought to be present: for a maximum disc solution the number of arms, calculated on the assumption that $X = 2$, is too low. However, in the rising parts of the rotation curve $\Gamma$ is less than 1.0, so that the $X$-value corresponding to maximum amplification is less than 2.

Mihos, McGaugh & De Blok (1997) apply the same notions of stability criteria to the Low Surface Brightness (LSB) galaxies. Since these are thought to be dark matter dominated, the amplification of $m = 2$ structures in those galaxies is much more difficult. Only interactions can trigger $m = 2$ disturbances, and even then the amplitudes are small and the deviations for axisymmetry not very large. However, the decomposition into disc and halo depends crucially on the correct determination of the rotation curve in the inner parts, and, as shown by De Blok (this meeting), the data for the LSB galaxy UGC 128 show that its disc is not necessarily dark matter dominated in the inner parts.

3.3. Flocculent and grand design galaxies

Elmegreen & Elmegreen (1990) made a statistic based on an extended gradient in the rotation curve, and compared this with their arm classes (Elmegreen & Elmegreen 1982). They concluded that there is a correlation between the two, in the sense that declining rotation curves are found in grand design spirals. From this they concluded that grand design spirals have smaller dark halos than flocculent galaxies.

Their interpretation, however, rests on their mixing large and small galaxies into only three bins, flocculent galaxies, intermediate galaxies, and grand design galaxies. A more detailed analysis can be done if one considers the width of the HI profile, corrected for inclination, with arm class. This has been done in Figure 3 for all the galaxies for which arm classes are available in Elmegreen & Elmegreen (1987) and HI profile data in Tully’s (1988) *Nearby Galaxy Catalog*. It can be seen that the galaxies in arm class 3 have high rotational velocities, which corresponds with their regular structure. Combining arm classes 1 - 4 into
one bin called “flocculent” thus lumps together dwarf galaxies with rising curves and giant galaxies with slowly declining curves. The “grand design” galaxies (arm classes 9 & 12) are predominantly giant galaxies, and the intermediate classes (arm classes 5 - 8) also. In view of these biases, Elmegreen & Elmegreen’s (1990) conclusions cannot be sustained.

3.4. Declining rotation curves

Rotation curves which drop relatively sharply beyond the optical radius and stay more or less flat thereafter, might, because of the additional identifiable feature, hold out a promise to enable us to discriminate between the various mass models. Since one expects them to be found amongst galaxies with high rotational velocities, I made a small survey with the VLA of a number of galaxies with $W_R > 400$ km/s in collaboration with Van Gorkom, Gunn, Knapp and Athanassoula. Several new cases of galaxies with such declining rotation curves were found. In Bosma (1998) a preliminary account is given for the most spectacular case, NGC 4414, for which also radial velocities and velocity dispersion information was obtained.

Unfortunately, the range in disc mass-to-light ratios for that galaxy cannot be constrained very easily, in spite of the feature. However, the velocity dispersion data allow the evaluation of the Toomre Q-parameter, which is found to be about 1.15 for a maximum disc model, but 2.30 for a “no $m = 2$” model. The latter value is definitely too high to allow spiral structure from swing amplification. A weak global spiral pattern is present in the old disc (Thornley 1996).
Therefore, it seems unlikely that the inner parts of bright disc galaxies are dark matter dominated.

Another spectacular case of a declining rotation curve has been reported for NGC 157 by Ryder et al. (1998). The strong warp and the relatively low inclination of the HI envelope make the determination of the rotation curve a bit uncertain, but there is a definite decoupling between the inner disc and the outer halo as traced by the HI.

4. Velocity dispersions

4.1. NGC 3198 once more

Bottema (1993), from an analysis of velocity dispersions, claims that the maximum velocity of the disc component is 63% of the maximum observed velocity. The path to this result is strewn with assumptions, the most important of which are that discs are exponential with a velocity ellipsoid close to that in the solar neighbourhood, that Freeman’s (1970) law holds, and that \((B-V)_{\text{old disc}} = 0.7\) for all discs. As already discussed above, for NGC 3198 Bottema’s result corresponds closely to the “no \(m = 2\)” solution proposed by Athanassoula et al. (1987).

A quick re-evaluation of Bottema’s result can be formulated as follows. From the good agreement between the stellar and gas rotation data presented in Bottema (1988), it follows that the asymmetric drift in NGC 3198 is small, and thus the epicyclic approximation can be used. This states that \(\kappa/2 \Omega = \sigma_\phi/\sigma_R\), where \(\Omega\) is the angular velocity, \(\kappa\) is the epicyclic frequency, and \(\sigma_R\) and \(\sigma_\phi\) are respectively the radial and azimuthal velocity dispersion. From the measurement of the rotation curve and the velocity dispersion along the major axis, ignoring the z-axis contribution for the moment, we can then calculate the radial velocity dispersion \(\sigma_R\) as function of radius, and from the mass model we can calculate the critical radial velocity dispersion needed for axisymmetric stability. The ratio between these two is Toomre’s (1964) parameter \(Q\):

\[
Q = \frac{\sigma_R}{\sigma_{\text{crit}}} = \frac{\sigma_R \kappa}{3.36G \mu}
\]  

(3)

For NGC 3198 we then find for the “maximum disc” model a mean \(Q\) of 0.92, and for a “no \(m = 2\)” model a mean \(Q\) of 1.92. The real uncertainties in these values are about 20%. The important result is that indeed for NGC 3198 the measured velocity dispersion seems too low to have a stable “maximum disc” solution (see also Fuchs’s contribution in this volume).

One can argue with this in several ways. First of all, the observed major axis velocity dispersion is a combination of \(\sigma_\phi\) and \(\sigma_z\), so the determination of \(\sigma_R\) may not be entirely correct.

Second, the numerical factor 3.36, which corresponds to a Schwarzschild distribution of the random velocities in an infinitesimally thin disc, should perhaps be corrected for the effect of thickness, possibly also for a different shape of the distribution function, and certainly for the effect of the gas which is important for a late type spiral. The thickness correction alone (calculated assuming all the material in the disc, and the solar neighbourhood value for the ratio of vertical to radial velocity dispersions) lowers the numerical factor to 2.6 (cf.
Shu 1968, Vandervoort 1970) and the effect of 10% of gas enhances then the factor to about 2.9 (cf. Toomre 1974). Other distribution functions may apply: Fuchs & Von Linden (1998) rediscuss and extend work by Graham (1967) and by Toomre (unpublished) on an exponential distribution function, for which the numerical factor is 3.944 instead of 3.36, so that with the thickness and 10% gas corrections we end up at 3.40. From Graham’s (1967) Figure 1, where he shows results for several other distribution functions, it becomes clear that the uncertainty in the numerical factor could be easily 20 - 30%.

Finally, as argued by Kormendy (priv. comm., see also discussion after Fuchs’s contribution), the influence of younger stellar populations in the spectra could result in lower measured velocity dispersions. In view of all these arguments, perhaps we should not be overly worried about the result that Q is just below 1.00 in NGC 3198.

4.2. Other galaxies

As discussed already above, for NGC 4414 I find a mean Q of about 1.15 for a “maximum disc” model, and about 2.30 for a “no $m = 2$” model. For NGC 2841, a preliminary analysis shows that for a “maximum disc” model $Q \simeq 1.5 - 1.6$, so that here a “no $m = 2$” model is dynamically too hot to be acceptable. Further work on other galaxies is in progress. In all cases, spectra are taken along the minor and the major axes, since only their combination can help us disentangle the radial, azimuthal and perpendicular velocity dispersions (cf. work on NGC 488 by Gerssen et al. 1997). It is hoped that with such data, a clearer answer can be given to the question whether the disc is close to “maximum disc” or not.

5. Halo parameters

Once halo parameters are derived, what can one do with them? Scaling relations between the halo parameters have been reviewed by Kormendy (1988), partly on the basis of the “no $m = 1$” models and results of Athanassoula et al. (1987). Apart from relatively obvious correlations, e.g. between $V_{\text{max, disc}}$ and the velocity dispersion of the halo, there are a few which are intriguing, such as the (weak) relation between the ratio of halo core radius and optical radius with Hubble type, and the correlation between halo core radius and central density of the halo for Sc - dwarf galaxies. These relations will be further investigated (Kormendy, priv. comm.).

Bosma (1991) shows that the frequency of warps, which is at least 50% for all spirals, depends on the ratio of halo core radius to optical radius of the galaxy: galaxies for which this ratio is small do not have warped HI discs. This is usually attributed to dynamical friction between a misaligned disc and a dark halo. If the dark halo is strongly concentrated, such misalignments are short lived, as is shown also by numerical simulations (Dubinski & Kuijken 1995).

Finally, Navarro (1998) uses the information on a concentration index, derived by fitting a functional form to the observed rotation curves, to argue that dwarf galaxies are too concentrated for a standard CDM $\Omega = 1$ model, but favour instead cosmological models with $\Omega < 1$.

Acknowledgments. I would like to thank Lia Athanassoula for fruitful discussions and comments on a draft of this paper. I gratefully acknowledge dis-
cussions with James Binney, Burkhard Fuchs, John Kormendy, Jerry Sellwood and Peter Vandervoort concerning some of the topics raised in this review.

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