The Amount of Dark Matter in Spiral Galaxies

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Abstract. The ‘maximum’ disk hypothesis of galactic disks imbedded in dark matter halos is examined. First, decompositions of the rotation curves of NGC 2613, 3198, 6503, and 7184 are analyzed. For these galaxies the radial velocity dispersions of the stars have been measured. If the parameters of the decompositions are chosen according to the ‘maximum’ disk hypothesis, the Toomre Q stability parameter is systematically less than one, which is a strong argument against the ‘maximum’ disk hypothesis. Next, density wave theory arguments are used to describe the morphology of the spiral arms of NGC 3223, 157, and 7083. It is shown that the ‘maximum’ disk hypothesis is not consistent with the observed morphologies of the galaxies.

1 Introduction

An important aspect of the dark matter problem of spiral galaxies is the question to what extent the galaxies are dominated by dark matter even in their inner parts, where the optically visible disks reside. The presence of dark matter is usually deduced from the decompositions of the rotation curves of the galaxies. These are, however, highly ambiguous, and ‘maximum’ disk versus submaximal disk decompositions of the rotation curves of spiral galaxies have been discussed at great length in the literature. The general opinion is that the inner parts of the galaxies are not dominated by dark matter (cf. Bosma (1999) for a recent review). However an increasing number of arguments have been put forward, which challenge this conclusion:

- Considerations of the formation of the baryonic disks in dark halos by dissipational collapse show that a considerable amount of dark matter is also pulled into the inner parts during this process (Blumenthal et al. 1985).
- Gravitational lensing of a quasar by the spiral edge-on galaxy B1600+434 indicates that its disk is submaximal (Maller et al. 2000).
- Courteau & Rix (1999) have used the Tully–Fisher relation to study with a large set of galaxies the statistical correlation of the peaks of the rotation curves of the galaxies with the radial scale lengths $h$ of the disks. They find a dependency $v_c \propto h^{-1/2}$, which cannot be the case, if the galaxies were dominated by dark matter.
- Kranz & Rix (cf. their contribution in this volume) have searched for the signatures of spiral arms in the rotation curve of NGC 4254 and conclude that its disk is submaximal.
On the other hand, based on numerical simulations of the slowing down of the rotation of bars in disks imbedded in dark matter halos, Debattista & Sellwood (1998) contend vociferously that galactic disks must be massive. Tremaine & Ostriker (1999) have made the suggestion that this problem could be possibly overcome, however, if the inner part of the dark halo is rotating, although Debattista & Sellwood (2000) claim that this would have to be at a level inconsistent with the low rotation of the stellar halos of galaxies. In addition Weiner et al. (2000) find by modelling the velocity field of the barred galaxy NGC 4123 a high mass-to-light ratio for its bar. Thus arguments concerning the amount of dark matter in galaxies are at present highly controversial.

The aim of this paper is to draw attention to the implications of the modelling of the rotation curves for the internal dynamics of the disks, which are related to the dynamical stability of the disks and the morphological appearance of the spiral structure of the galaxies.

The sample of galaxies used here to study their dynamical stability has been drawn from the list of Bottema (1993) of galaxies with measured stellar velocity dispersions. The criteria were (a) that the rotation curve of each galaxy, preferentially in HI, is observed, (b) that each galaxy is so inclined that the planar velocity dispersions are measured, but (c) that the spiral structure is clearly discernible (cf. also Fuchs 1999).

In section 3 density wave theory arguments will be used to describe the morphology of the spiral arms of NGC 3223, 157, and 7083, for which NIR photometry and rotation curves are available (Block et al. 2000). This provides again constraints on the decomposition of the rotation curves of the galaxies.

## 2 Decomposition of the rotation curves and the Q parameter as diagnostic tool

The rotation curve of each galaxy is fitted by the superposition of contributions due to the stellar and gaseous disks, both modelled by thin exponential disks, in the case of NGC 2613 a bulge, modelled by a softened $r^{-3.5}$ density law, and the dark halo, modelled by a quasi-isothermal sphere,

$$v_c^2(R) = v_{c,d}^2(R) + v_{c,g}^2(R) + v_{c,b}^2(R) + v_{c,h}^2(R). \quad (1)$$

Detailed formulae for each of the contributions in (1) can be found, for instance, in Fuchs, Möllenhoff & Heidt (1998). The radial scale lengths of the disks, $h$, and core radii of the bulges, $r_{c,b}$, as well as the bulge to disk ratios have been adopted from published photometry of the galaxies (cf. Bottema (1993), Broeils (1992) and references therein). Only in the cases of NGC 3198 and 6503 HI data were available, which allowed the determination of the $v_{c,g}$ contribution in (1). No quantitative photometry of the bulge of NGC 7184 is available.

The diagnostic tool, which I use to analyze the rotation curve models, is the Toomre stability parameter of the disks, which is given by

$$Q = \frac{\kappa \sigma_U}{3.36 G \Sigma_d}. \quad (2)$$
Fig. 1. ‘Maximum’ disk decomposition of the rotation curve of NGC3198. The contributions to the rotation curve due to the various components are indicated. The inferred stability parameter is shown in the left panel.

Fig. 2. ‘Maximum’ disk decomposition of the rotation curve of NGC6503.

Fig. 3. ‘Maximum’ disk decomposition of the rotation curve of NGC2613.

In (2) \( \kappa \) denotes the epicyclic frequency, which can be directly derived from the rotation curve, \( \sigma_U \) the measured radial velocity dispersion of the stars, \( G \) the constant of gravitation, and \( \Sigma_d \) the surface density of the disk, which follows from the fits to the rotation curves. The stability parameter must lie in the range \( 1 < Q < 2 \), in order to prevent Jeans instability of the disk, on one hand, and to allow the disks to develop spiral structures, on the other hand.

Decompositions of the rotation curves of the galaxies, which maximise the disk contribution in (1), are shown in Figs. 1 to 4 together with the resulting
As can be seen from the figures, the \( Q \) parameters are systematically close to or even less than one. That is impossible in real galactic disks. As is well known since the classical paper by Sellwood & Carlberg (1984), the disks would evolve fiercely under such conditions and heat up dynamically on short time scales. If the model of Sellwood & Carlberg is scaled to the dimensions of NGC 6503, the numerical simulations indicate that the disk would heat up within a Gyr from \( Q = 1 \) to 2.2 and any spiral structure would be suppressed (cf. also Fuchs & von Linden 1998). The amount of young stars on low velocity dispersion orbits, which would have to be added to the disk in order to cool it dynamically back to \( Q = 1 \), can be estimated from (2). In NGC 6503 a star formation rate of 40 \( M_\odot/pc^2/Gyr \) would be needed, while actually a star formation rate of 1.5 \( M_\odot/pc^2/Gyr \), as deduced from the H\( \alpha \) flux (Kennicutt et al. 1994), is observed. Thus ‘maximum’ disks seem to be unrealistic under this aspect.

This deficiency can be remedied, if submaximal disks are assumed. This is illustrated in Fig. 5 for NGC 3198, where the mass-to-light ratio of the disk has been reduced from \( M/L_B = 3.5 \) to 2.2 \( M_\odot/L_B,\odot \). Within the optical radius the dark halo contributes twice the mass of the disk and its core radius is of the order of the radial scale length of the disk. As can be seen in Fig. 5 and similarly in Fig. 6 for NGC 6503, the \( Q \) parameters lie in a more realistic range. There is,
however, a caveat about the interpretation of velocity dispersion measurements in galactic disks that contain young stars. The problem is that stars that dominate the spectra are relatively bright, young and have comparatively low velocity dispersions, whereas the stars that dominate the disk mass are older and less luminous, but have higher velocity dispersions. For the Galactic disk this effect can be estimated quantitatively using data from the solar neighbourhood (Jahreiß, Wielen, & Fuchs 1998). A detailed analysis shows that the luminosity-weighted, scale–height corrected radial velocity dispersion of stars in the Galactic disk is $\sigma_U = 36$ km/s, which has to be compared with 44 km/s of the old disk stars. The weight of young stars is 25% of the total weight. In Sc galaxies, which are bluer than the Galaxy with an averaged $\langle B-V \rangle$ of 0.66 mag, this might be shifted even more towards young stars. On the other hand, Sc galaxies are more gas rich, which has a destabilizing effect. Taken all together, the $Q$ argument seems to be quite robust.

3 Spiral density wave theory constraints on the decomposition of rotation curves

The morphology of spiral galaxies is described theoretically by the density wave theory of galactic spiral arms. One of the predictions of the theory is that spiral density waves with a circumferential wave length of

$$\lambda = X \left( \frac{dv}{dR} \right) \cdot \lambda_{\text{crit}} = X \left( \frac{dv}{dR} \right) \cdot \frac{4\pi^2 G \Sigma_d}{\kappa^2}$$

have the largest growth rate and will dominate the morphological appearance of the disk (Toomre 1981).
Fig. 8. Theoretical model of the spiral arms of NGC 3223 (Block et al. 2000). The $x$-axis points radially outwards and the $y$-axis in the tangential direction. Length unit is $\lambda_{\text{crit}}$. The contours are given in arbitrary units. The disk is bounded at the left side ($x = -x_0$) by the massive bulge of the galaxy.

The value of the $X$ parameter is about 2 in the case of a flat rotation curve, but less for rising rotation curves (Athanassoula et al. 1987, Fuchs 1999). The expected number of spiral arms is given by

$$m = \frac{2\pi R}{\lambda}. \quad (4)$$

Block et al. (2000) have presented theoretical models based on the work of Fuchs (2001, in preparation) for the spiral arms of the galaxies NGC 3223, 157, and 7083, for which NIR photometry and rotation curves are available. The epicyclic frequency and the value of the $X$ parameter have been obtained directly from the observed rotation curves for each galaxy. The spiral arms of all three galaxies are very regular and clearly defined in the NIR (see Block et al. 2000 for images). Equations (3) and (4) can be then used to determine the surface densities of the disks, modelled again by thin exponential disks. NGC 3223 is a good example to illustrate the constraint on the disk mass obtained this way from the morphology of the galaxy in some more detail. In Fig. 7 a NIR image is reproduced and in
Fig. 8 the theoretical model of the spiral arms of the galaxy is shown, where the same value of Oort’s constant $A/\Omega_0$ as in the optical part of NGC 3223 has been adopted. The theoretical model, which has been calculated in rectangular coordinates, has to be imagined to be folded around the galactic center of the galaxy. Since NGC 3223 has two well defined spiral arms, this constrains the critical wave length $\lambda_{\text{crit}}$ according to (3) and (4). This, in turn, determines the surface density of the disk. Together with the radial scale length of the disk measured by Grosbøl and Patsis (1998) this allows finally to calculate the disk rotation curve (cf. (1)) shown in Fig. 9. Obviously the disk of NGC 3223 is submaximal, and the same is also found for the two other galaxies.

![Fig. 9. Rotation curve of NGC3223. The observed data are indicated by the symbols and the disk contribution to the rotation curve is shown by the dotted line.](image)
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