NGC 2613, 3198, 6503, 7184: Case studies against 'maximum' disks

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Abstract. 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 and their morphology is clearly discernible. If the parameters of the decompositions are chosen according to the 'maximum' disk hypothesis, the Toomre Q stability parameter is sytematically less than one and the multiplicities of the spiral arms as expected from density wave theory are inconsistent with the observed morphologies of the galaxies. The apparent $Q \lesssim 1$ instability, in particular, is a strong argument against the 'maximum' disk hypothesis.

1. Introduction

'Maximum' disk versus submaximal disk decompositions of the rotation curves of spiral galaxies have been discussed at great length in the literature (cf. the articles by Bosma and Sellwood in this volume). The aim of this paper is to draw attention to the implications of such models of the rotation curves for the internal dynamics of the disks.

The sample of galaxies studied here has been drawn from the list of Bottema (1993) of galaxies with measured stellar velocity dispersions. The criteria were: (a) the rotation curve of each galaxy, preferentially in HI, is observed, (b) each galaxy is so inclined that the planar velocity dispersions are measured, but (c) that its morphology is still discernible.

2. Decomposition of the rotation curves and diagnostic tools

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, the bulge (NGC 2613 only), modelled by a softened $r^{-3.5}$ density law, and the dark halo, modelled by a quasi-isothermal sphere,

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

The radial scale lengths of the disks, h, and core radii of the bulges, $r_{\mathrm{c,b}}$, 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 $v_{\mathrm{c,g}}$ contribution in Eq. (1). No quantitative photometry of the bulge of NGC 7184 is available.

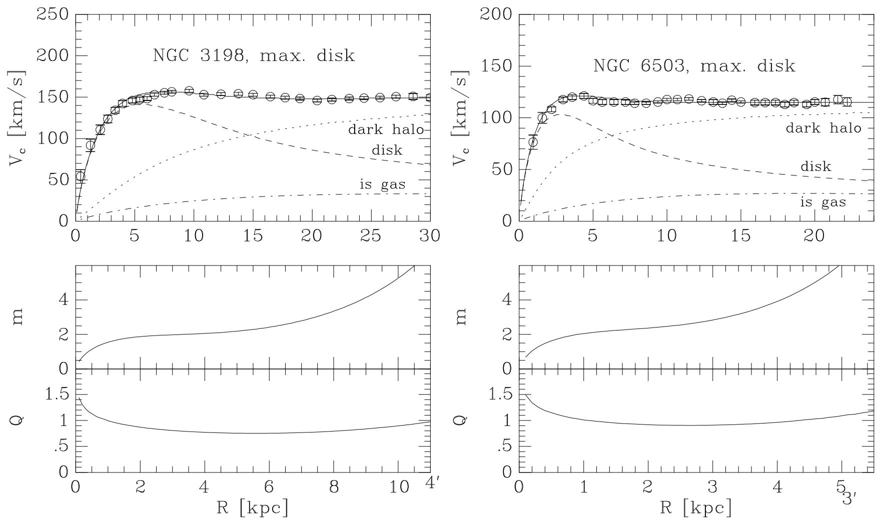


Figure 1. 'Maximum' disk decompositions of the rotation curves. The expected multiplicities of spiral arms and the stability parameters are shown in the lower panels.

The diagnostic tools, which I use to analyze the rotation curve models, are the Toomre stability parameter of the disks and, following Athanassoula et al. (1987), the predicted multiplicity of the spiral structures. The Toomre stability parameter is given by

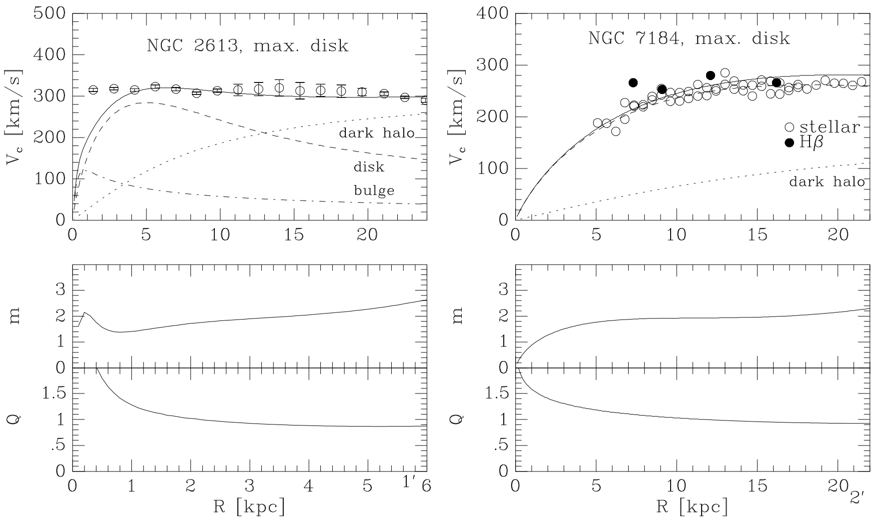
$$Q = \frac{\kappa \sigma_{\rm U}}{3.36 G \Sigma_{\rm d}}. \tag{2}$$

In Eq. (2) κ denotes the epicyclic frequency, which can be directly derived from the rotation curve, $\sigma_{\rm U}$ the – measured – radial velocity dispersion of the stars, G the constant of gravitation, and $\Sigma_{\rm d}$ 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. All the galaxies studied here are not grand-design spirals. In these galaxies the spiral structures are almost certainly due to 'swing amplification' of perturbations of the disks (Toomre 1981). This mechanism is most effective, if the circumferential wave length of the density waves is

$$\lambda = X\left(\frac{dv_{\rm c}(R)}{dR}\right)\lambda_{\rm crit} = X\left(\frac{dv_{\rm c}(R)}{dR}\right)\frac{4\pi^2 G\Sigma_{\rm d}}{\kappa^2}\,. \tag{3}$$

The value of the X parameter is about 2 in the case of a flat rotation curve, but less in the rising parts of the rotation curve (Athanassoula et al. 1987). I apply in Eq. (3) a relation for $X(\frac{dv_{\rm c}(R)}{dR})$ found by analyzing the stellardynamical equivalent of the Goldreich & Lynden-Bell sheet (Fuchs 1991). The expected number of spiral arms is given by $m = 2\pi R/\lambda$. Eq. (3) is derived from local density wave theory. Recent alternative approaches based on global analyses of non-axisymmetric perturbations of galactic disks are described by Haga & Iye (1994), Evans & Read (1998a, b), and Pichon & Cannon (1998).

Decompositions of the rotation curves of the galaxies, which maximise the disk contribution in Eq. (1), are shown in Figs. 1a and b together with the resulting stability parameters and expected multiplicities of spiral arms. As can be seen from Figs. 1 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. 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 Eq. (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_α flux (Kennicutt et al. 1994), is observed. Thus 'maximum' disks seem to be unrealistic under this aspect.



Furthermore, according to the 'maximum' disk models the galaxies should be two-armed spirals. This is in agreement with Athanassoula et al. (1987) and Haga (1998, private communication), who concluded that in NGC 3198 and 6503 m is at least two. However, as can be seen on images of the galaxies (cf. The Carnegie Atlas of Galaxies), all the galaxies discussed here have a multi-armed, irregular morphological appearrance.

Both deficiencies can be remedied simultaneously, if submaximal disks are assumed. This is illustrated in Fig. 2 for NGC 3198, where the mass-to-light ratio of the disk has been reduced from $M/L_{\rm B} = 3.5$ to 2.2 $M_\odot/L_{{\rm B},\odot}$. 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 from Fig. 2, the Q parameter lies in a more realistic range and the predicted multiplicity of spiral arms fits better to the observed morphology of the galaxy than in the 'maximum' disk model.

I am grateful to E. Athanssoula, A. Bosma, and J. Kormendy for valuable hints and discussions.

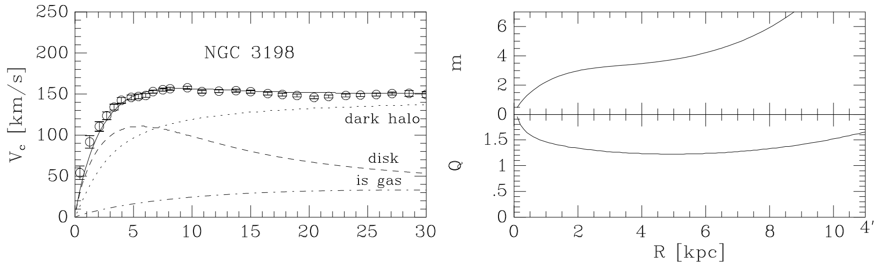


Figure 2. Decomposition of the rotation curve with a submaximal disk.

Discussion

Kormendy: I'm worried about the interpretation of velocity dispersion measurements in late-type disks that contain young stars. There is a danger that stars that dominate the spectra are relatively bright, young, and low in velocity dispersion and that the stars that dominate the disk mass are older, fainter and hotter. Our Galactic disk shows just such an effect. It would imply that measured dispersion values may be too small to correctly represent the disk mass in calculations of Q.

Fuchs: Yes, one has to keep this in mind. For the Galactic disk the effect can be estimated using data from the solar neighbourhood. A detailed analysis shows that the luminosity-weighted, scale-height corrected radial velocity dispersion of stars in the Galactic disk is $\sigma_{\rm U} = 36$ 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 $< B - V >$ 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.

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