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Decomposition of the rotation curves of distant field galaxies

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Abstract. We present decompositions of the rotation curves of distant spiral galaxies into contributions due to their bulges, disks, and putative dark haloes. In order to set constraints on the ambiguities of the decompositons we interpret the morphology of the spiral structures quantitatively in the framework of density wave theory. Galaxy models constrained in such a way show that the distant galaxies, which are much younger than nearby galaxies, are indeed also imbedded in dark haloes as expected from contemporary theories of the cosmogony of galaxies.

Key words: Galaxies: individual: – Galaxies: kinematics and dynamics – *(Cosmology:)* dark matter

1. Introduction

Vogt et al. (1996; hereafter referred to as VFP) have determined recently by spectroscopy with the Keck telescope optical rotation curves of a sample of distant field galaxies. They present also quantitative photometry of the surface brightness of the galaxies using images taken with HST. These data allow first insight into the dynamics of distant spiral galaxies, which are much younger than nearby galaxies. Contemporary theories of the cosmogony of galaxies predict that these galaxies will be imbedded in dark haloes like nearby galaxies, because the dark haloes are thought to be the sites of galaxy formation. The data by VFP provide the first chance to search directly for evidence of such dark haloes around distant galaxies. Quillen & Sarajedini (1998) have pointed out that the morphology of the disks of that galaxies, especially their spiral structure, can be used to constrain the dynamical properties of the disks. They concentrated on estimating the mass – to – light ratios and the velocity dispersions of the galactic disks. In this study we wish to demonstrate how the morphological appearance of the spiral structure of the disks may be used to constrain the otherwise ambiguous decomposition of the rotation curves of the galaxies.

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Two galaxies in the sample of VFP, VFP J074-2237 at a redshift of z = 0.15 and VFP J0305-00115 at a redshift of z = 0.48, have clearly evident, prominent spiral structures. There is a further interesting galaxy, VFP J064-4442 at a redshift of z = 0.88, which shows indications of spiral structure. However, the signal – to – noise level is too low to resolve the structures well enough for a quantitative analysis.

In sections 2 and 3 we construct dynamical models for the two medium – redshifted galaxies and discuss implications of the evidence for the presence of dark matter in the galaxies in the final section.

2. Bulge – disk decompositions

In the case of VFP J0305-00115 we adopt the decomposition of the surface brightness distribution of the galaxy into bulge and disk components, respectively, given by Forbes et al. (1996). The disk is fitted by the surface brightness profile of an exponential disk,

$$\Sigma_{\rm d}(R) = \Sigma_{\rm d0} \exp(-R/h)\,, \tag{1}$$

with an extrapolated central surface brightness of 20.9 mag/arcsec^2 in the I band and, adopting a scale conversion factor of 5.25 kpc/arcsec, a radial scale length of h = 5.1 kpc. The bulge has been fitted by Forbes et al. (1996) by a de Vaucouleurs profile with an effective radius of $R_{\rm e}$ = 0.8 kpc and a surface brightness of 20.5 mag/arcsec^2 in the I band at radius $R_{\rm e}$. For reasons of easier handling of the dynamical models we have used instead of a de Vaucouleurs law the surface brightness profile of a bulge model with a density distribution of the form

$$\rho_{\rm b}(r) = \rho_{\rm b0}\left(1+\frac{r^2}{r^2_{\rm c,b}}\right)^{-\frac{3.5}{2}}\,. \tag{2}$$

The surface brightness profile follows a similar law with the exponent lowered by 1/2. We have fitted such a surface brightness profile to the de Vaucouleurs law over the distance range $R = 0.1$ to 0.6 arcsec, where the surface brightness of the galaxy is dominated by the bulge (Forbes et al. 1996), and find that the de Vaucouleurs law can be fitted with an accuracy better than 0.05 mag/arcsec^2. We determine in this way a core radius of $r_{\rm c,b} = 2.8$ kpc and a central surface brightnes of 20.4 mag/arcsec^2.

The photometric parameters of VFP J074-2237 have been only partially published up to now. We have therefore retrieved its I band images from the HST archive (prop. id. 5109) and have fitted the two – dimensional surface brightness distribution of a highly inclined (i = 80°) exponential disk and a bulge with a surface brightness profile according to equation (2) to the data using the code of Möllenhoff (1998). Although the fit is hampered somewhat by the very prominent spiral structure, we find a radial disk scale length of $h = 3.4$ kpc, if a scale conversion factor of 2.41 kpc/arcsec is assumed, which is in excellent agreement with the value given by VFP. The surface brightness of the bulge is low. The central surface brightness of the disk is brighter by 3.2 mag/arcsec^2 than the central surface brightness of the bulge. Thus we neglect the contribution by the bulge in the following.

3. Decomposition of the rotation curves

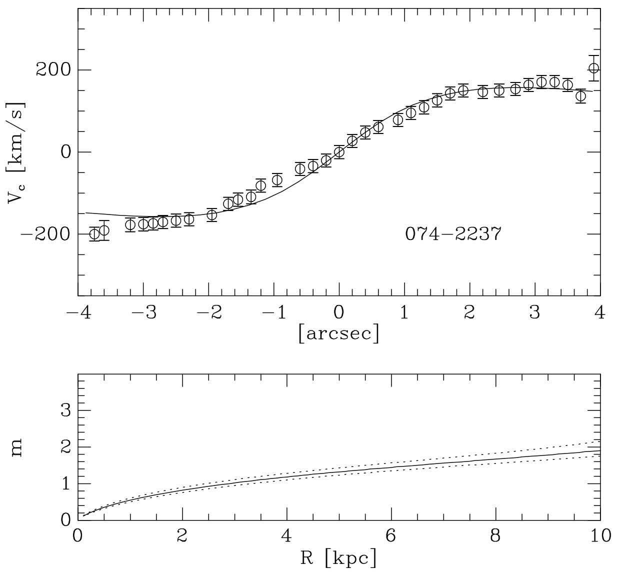

Fig. 1. Upper panel: Model rotation curve of VFP J074-2237 fitted to the radial velocity data of VFP. Lower panel: Number of expected spiral arms. The dotted lines indicate error estimates.

Due to the comparatively large width of the slit of the spectrograph VFP have not observed directly the rotation curves of the galaxies. But they use a simple model of the velocity fields of the disks in which the circular velocity is assumed to rise linearly with radius up to one radial disk scale length and then to remain flat. Folded with the surface brightness distribution and averaged over the area of the slit such models can be excellently fitted to the observed data. We adopt model rotation curves of the form

$$v_{\rm c}^2(R) = v_{\rm c,b}^2(R) + v_{\rm c,d}^2(R)\,, \tag{3}$$

where $v_{\rm c,b}$ and $v_{\rm c,d}$ denote the contributions due to the bulge and disk, respectively. The bulge contribution is given according to equation (2) by

$$v_{\rm c,b}^2(R) = \frac{4\pi G\rho_{\rm b0}}{R}\int_0^R dr r^2 \left(1+\frac{r^2}{r_{\rm c,b}^2}\right)^{-\frac{3.5}{2}}\,, \tag{4}$$

where G denotes the constant of gravitation. The rotation curve of an infinitesimally thin exponential disk is given by

$$v_{\rm c,d}^2(R) = 4\pi G\Sigma_{\rm d0} h x^2 \left(I_0(x)K_0(x) - I_1(x)K_1(x)\right)\,, \tag{5}$$

where $\Sigma_{\rm d0}$ denotes now the central face-on surface density of the disk. x is an abbreviation for $x = R/2h$ and I and K are Bessel functions (cf. Binney & Tremaine 1987). The model rotation curves have been treated in the same way as by VFP. The velocity fields and the emission-line surface brightness were projected onto the sky adopting the inclination angles determined by VFP. As suggested by VFP, the emission-line surface brightness profiles were approximated by exponential disks with radial scale lengths 1.5 times that measured from the HST images. The models were then convolved with Gaussians in order to model the blurring of the velocity fields by seeing, which VFP estimate as 1 and 0.8 arcsec (FWHM) in the cases of VFP J074-2237 and VFP J0305-00115, respectively. Finally the models were masked according to the slit positions indicated in Fig. 1 of VFP. Fits of model rotation curves obtained in this way to the observed radial velocities are shown in Figs. 1 and 2 and the resulting parameters are summarized in Table 1. VFP estimate that the uncertainties of the radial scale lengths determined from the HST images are about 15%. We find that in the case of VFP J035-00115 the radial velocities within 1 arcsec from the center of the galaxy can be fitted better, if we use instead of the value given by Forbes et al. (1996) a radial scale length reduced by 15% to 4.3 kpc, which we adopt for our dynamical models.

We have chosen both galaxies because of their clearly discernible spiral structure. In order to be able to develop spiral structure galactic disks must be dynamically cool enough, i.e. the Toomre stability parameter Q (cf. Binney & Tremaine 1987) must lie in the range (Quillen & Sarajedini 1998)

$$1 < Q = \frac{\kappa\sigma_{\rm U}}{3.36 G\Sigma_{\rm d}} \lesssim 2\,, \tag{6}$$

Table 1. Dynamical parameters

VFP	ρ_{b0}	Σ_{d0}	ρ_{h0}	$M_{\mathrm{lum}}/M_{\mathrm{dark}}$ [a]	M/L_{B}
074-2237	–	1400	–	–	3.9
	–	850	0.025	1.0	2.4
0305-00115	0.21	800	–	–	4.8
	0.16	600	0.016	2.1	3.6
	$M_\odot$ pc^{-3}	$M_\odot$ pc^{-2}	$M_\odot$ pc^{-3}		$M_\odot$ $L_{\mathrm{B}\odot}{}^{-1}$

[a] Within radius $R = 10$ kpc.

where κ, $\kappa^2 = 2\left(\frac{v_c}{R}\right)^2\left(1+\frac{dln v_c}{dln R}\right)$, and σ_{U} denote the epicyclic frequency and the radial velocity dispersion of the stars, respectively. Furthermore, both galaxies are not grand – design spirals. Thus their spiral arms are almost certainly formed during 'swing – amplification' events (Toomre 1981). This mechanism is most effective, if the circumferential wave length of the density waves is twice the critical wave length,

$$\lambda = 2\lambda_{\mathrm{crit}} = \frac{8\pi^2 G\Sigma_{\mathrm{d}}}{\kappa^2}\,. \tag{7}$$

The expected number of spiral arms is then

$$m = \frac{2\pi R}{\lambda}\,. \tag{8}$$

The multiplicity of spiral arms has been discussed previously using similar arguments by Athanassoula (1988), Athanassoula et al. (1987), or Fuchs et al. (1996). As shown in the lower panels of Figs. 1 and 2 the predicted number of spiral arms is less than two, which is in clear contradiction to the morphological appearance of the galaxies. Both have bisymmetric spiral arms in the inner parts of the disks and additional filaments in the outer parts (cf. Fig. 1 of VFP). In the case of a single exponential disk the amplitude of the rotation curve cancels out of equation (7), and thus the determination of m. The only remaining uncertainty is then due to the uncertainty of the radial scale length h. This is illustrated for VFP J074-2237 in the lower panel of Fig. 1 by dotted lines.

Since it is generally expected that distant galaxies are imbedded in dark haloes like nearby galaxies, we have also considered an additional dark halo component in the decomposition of the rotation curves. The dark haloes are modelled by quasi – isothermal spheres,

$$\rho_{\mathrm{h}}(r) = \rho_{\mathrm{h0}}\left(1+\frac{r^2}{r_{\mathrm{c,h}}^2}\right)^{-1}\,, \tag{9}$$

which leads to a further term,

$$v_{\mathrm{c,h}}^2(R) = 4\pi G\rho_{\mathrm{h0}} r_{\mathrm{c,h}}^2\left(1-\frac{r_{\mathrm{c,h}}}{R} arctan\frac{R}{r_{\mathrm{c,h}}}\right)\,, \tag{10}$$

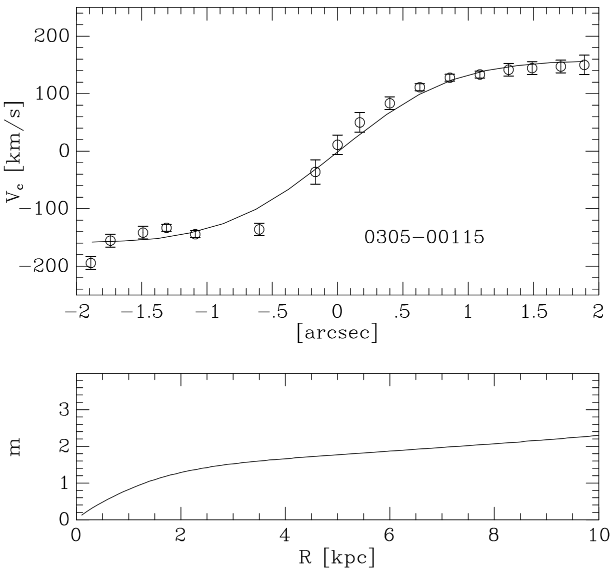

Fig. 2. Upper panel: Model rotation curve of VFP J0305-00115 fitted to the radial velocity data of VFP. Lower panel: Number of expected spiral arms.

in equation (3). Unfortunately, the rotation curves span radially only two or three disk scale lengths. As is well known from nearby galaxies, the disk and dark halo parameters are not well constrained in such cases (van der Kruit 1995). We have experimented with a variety of possible decompositions of the rotation curves and find a tendency that in near 'maximum' disk decompositions the central densities of the dark haloes is low and their core radii are large and reverse in 'medium' disk decompositions. From these we have selected models in which the expected number of spiral arms is in accordance with the observed morphology of the galaxies. In Figs. 3 and 4 models are illustrated with core radii of the dark haloes twice the radial disk scale lengths, which provide fits to the observed data of the same quality as the single disk or disk – bulge models shown in Figs. 1 and 2. The central densities are listed in Table 1. The disks contribute at the peaks of the disk rotation curves 76% and 70% to the composite rotation curves of VFP J074-2237 and VFP J0305-00115, respectively. Similar decompositions of the rotation curves of nearby galaxies have been suggested by Bottema (1998).

4. Discussion and Conclusions

We conclude that the interpretation of the morphology of the distant galaxies gives circumstantial but significant evidence for the presence of dark haloes. The galaxies are, however, in the parts observed by VFP not dominated by dark matter as can be seen from column (5) of Table 1. This is quite similar to those nearby galaxies which have been studied only with optical rotation curves (Broeils

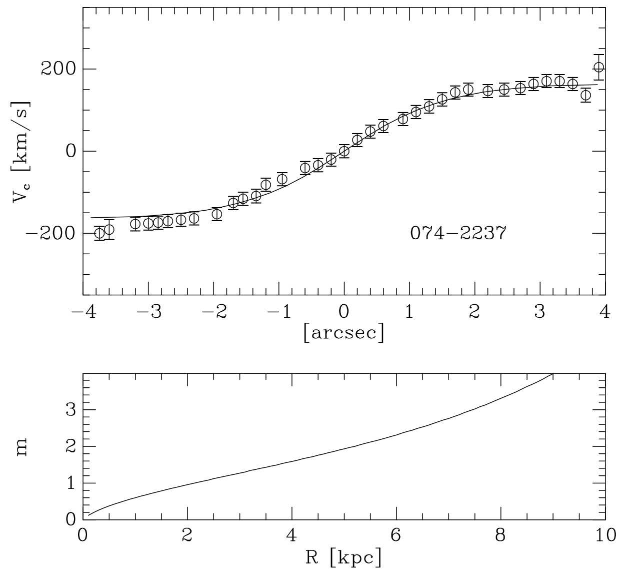

Fig. 3. Upper panel: 'Medium' disk decomposition of the rotation curve of VFP J074-2237. Lower panel: Number of expected spiral arms.

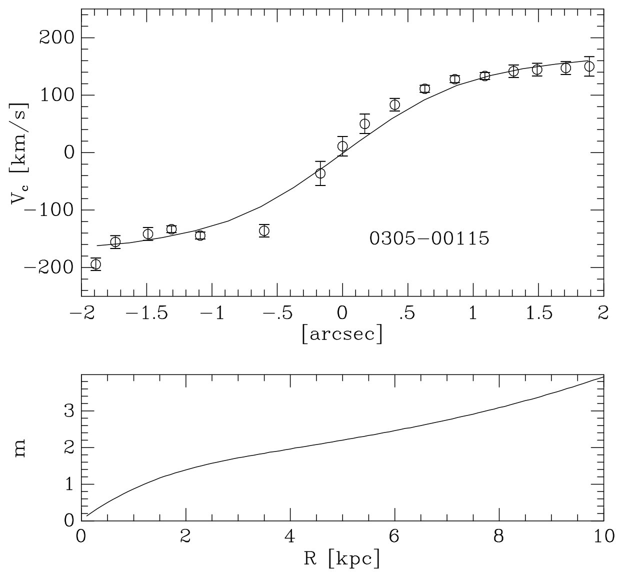

Fig. 4. Upper panel: 'Medium' disk decomposition of the rotation curve of VFP J0305-00115. Lower panel: Number of expected spiral arms.

1992). Using the rest frame luminosities given by VFP we have determined the mass – to – light ratios listed in the last column of Table 1. The maximum disk mass – to – light ratios lie at the upper end of the range determined by Broeils (1992) and Broeils & Courteau (1997) by maximum disk decompositions of rotation curves of bright nearby spiral galaxies. Because of the dynamical implications explained in the previous section, we argue in favour of the lower mass – to – light ratios given in Table 1.

Following Quillen & Sarajedini (1998) we discuss finally constraints set by the Toomre stability parameter. In Fig. 5 the radial variation of the ratio $\sigma_{\rm U}/Q$ is shown, which has been calculated according to equation (6) for both galaxies using the 'medium' disk parameters given in Table 1. According to density wave theory the stability parameter must lie in the range $1 < Q \,\tilde{<}\, 2$ (Toomre 1981). Thus we predict for the disk of VFP J074-2237 at the radius $R = h$ a radial velocity dispersion of the stars in the range $\sigma_{\rm U}$ = 54 to 108 km/s, and similarly for VFP J0305-00115 $\sigma_{\rm U}$ = 42 to 84 km/s. We note that these values fit nicely to velocity dispersions observed in the disks of nearby galaxies. Bottema (1993) finds in nearby galaxies that on the average $\sigma_{\rm U}$ = -17$\cdot$M$_{\rm B,disk}$ - 279 km/s at $R = h$, which would imply 87 km/s for VFP J074-2237 and 80 km/s for VFP J0305-00115, respectively, if the rest frame luminosities given by VFP are used. However, it remains at present unclear how the local velocity dispersion – magnitude relation can be extended to distant galaxies. It is generally believed that redshifted galaxies undergo some luminosity evolution. VFP find, for instance, that the Tully – Fisher relation defined by the galaxies of their

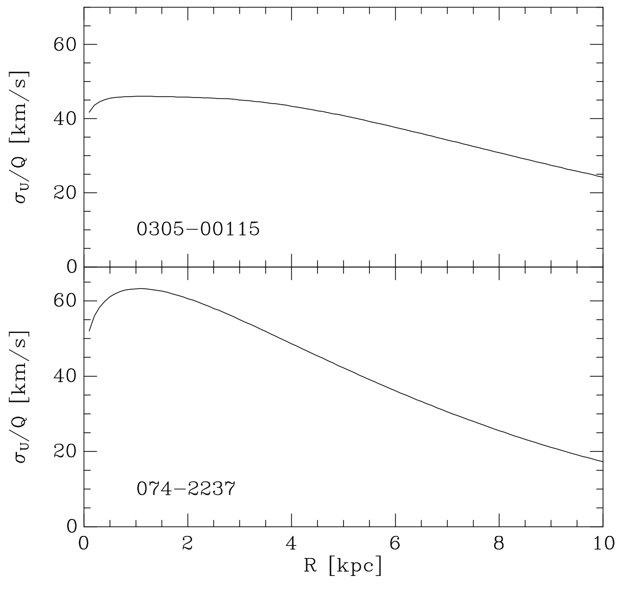

Fig. 5. Radial variation of the ratio of the radial velocity dipersion of the stars in the disks of the galaxies divided by the Toomre stability parameter Q. According to density wave theory the stability parameter is expected to lie in the range $1 < Q \,\tilde{<}\, 2$.

sample is shifted relative to the local Tully – Fisher relation by $\Delta M = 0.6$ mag in the sense that the redshifted galaxies are intrinsically brighter. If the velocity dispersion – magnitude relation is affected in the same way, the velocity dispersions predicted from this relation would be lower by 10 km/s, but still fully consistent with the velocity dispersions derived from stability arguments. If the 'maximum' disk parameters are inserted into equation (6), the predicted velocity dispersions increase by 30% to 40% and become unrealistically large as was previously noted by Quillen & Sarajedini (1998), who assumed 'maximum' disks. In the case of VFP J074-2237, for instance, the predicted velocity dispersion of the disk stars would be of the order of the expected velocity dispersion of halo stars, $v_{\rm c}/\sqrt{2} = 141$ km/s.

Quillen & Sarajedini (1998) have also pointed to the fact that the gaseous disks of the galaxies cannot be too massive, because they would otherwise be dynamically unstable, $Q_{\rm g} < 1$. Such gas disks would trigger very violent dynamical reactions both of the gaseous and the stellar disks (Fuchs & von Linden 1998). The disks would heat up on a very short time scale and the galaxies would change their morphology from well ordered spiral structure to a highly flocculent appearance. For VFP J074-2237 we find, again at the radius $R = h$, a value of the stability parameter of the gas disk of $Q_{\rm g}(R = h) = (\sigma_{\rm g}/54{\rm km/s})/f$, where f denotes the fraction of the total surface density of the disk in the form of interstellar gas. If we assume a velocity dispersion of the gas of $\sigma_{\rm g} = 6$ km/s, the gas fraction is restricted to values $f < 11\%$, although this may increase in the outer parts of the disk. We find for VFP J0305-00115 a similar low value of the gas fraction of $f < 14\%$ at the radius $R = h$.

We conclude that, taken all arguments together, distant spiral galaxies are indeed imbedded in dark haloes similar to those of nearby galaxies.

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