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Letter to the Editor

Quantitative interpretation of the morphology of NGC 1288*

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Abstract. We present a quantitative photometry of the bulge and disk of NGC 1288. We deduce from the multiplicity of spiral arms, using arguments of density wave theory, that NGC 1288 must be imbedded in a dark halo.

Key words: galaxies: individual: NGC 1288 – galaxies: kinematics and dynamics – galaxies: photometry – cosmology: dark matter

1. Introduction

NGC 1288 has been observed by the FORS team in the B–, V–, and I–filter pass bands (Möllenhoff et al. 1999; hereafter referred to as MAG). The unprecedented quality of the images allows a quantitative interpretation of the morphology of the galaxy. NGC 1288 has multiple spiral arms, which show up in all filter bands. It is well known from density–wave theory of galactic spiral arms (Bertin et al. 1977, Lau & Bertin 1978, Toomre 1981, 1990, Athanassoula 1984, Fuchs et al. 1998, Fuchs 1999) as well as from numerical simulations of galactic disks (Sellwood & Carlberg 1984, Carlberg & Freedman 1985) that the morphology of the spiral arms, i.e. the appearance and multiplicity of the spiral arms, is closely related to the ratio of disk mass to dark halo mass. Especially Athanassoula et al. (1987) have pointed to the fact that the multiplicity of spiral arms can be used as an indicator for the presence of a dark halo. This was confirmed observationally by Elmegreen & Elmegreen (1990), who correlated the shapes of the outer rotation curves of galaxies with the morphologies of their spiral arms. NGC 1288 is not a grand–design spiral. We argue here that its spiral structure is due to swing–amplification of shearing density waves (Toomre 1981). We have used arguments of swing–amplification density–wave theory to interpret the morphology of nearby spirals or distant field galaxies elsewhere (Fuchs et al. 1998, Fuchs 1999), and apply the same method here to the morphology of NGC 1288. It is the purpose of this letter to demonstrate that NGC 1288 must be surrounded by a dark matter halo. This is possible, even though the rotation curve of NGC 1288 is not known in detail.

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* Based on observations collected at the European Southern Observatory, Paranal, Chile (VLT UT1 Commissioning Program).

Table 1. Photometric parameters of NGC 1288

	μ_{I0}	B – I	$r_{0,b}$	h	α	i
Bulge	17.16	3.26	0.152	–	1.3	–
Disk	19.57	2.05	–	6	–	35
	mag/□”	mag	kpc	kpc		deg

2. Quantitative surface brightness photometry

We use the methods of two–dimensional image fitting as developed by MAG to model the surface brightness of NGC 1288 in a quantitative way. In Fig. 1 an I–band image is reproduced. The disk is fitted by an exponential density law,

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

where R denotes the galactocentric radius in the plane of the disk. The bulge is modelled by a spherical density distribution of the form

$$\rho_{\rm b} = \rho_{\rm bo}\left(1+\frac{r^2}{r_{0,\rm b}^2}\right)^{-\alpha}. \qquad (2)$$

The surface brightness profile follows a similar law with the exponent α lowered by 0.5. The resulting parameters are listed in Table 1. According to the radial velocity $v_{3\,\rm K}$ = 4405 km s^{-1} (RC3, de Vaucouleurs et al. 1991) of NGC 1288 we assume a distance of 60 Mpc. Thus 1$''$ corresponds to 290 pc or 1 kpc to 3.44$''$. Although we use a different bulge model than MAG, the quality of the fit is comparable to that of MAG.

As can be seen in Fig. 2 the residuals $\Delta\mu$ of the data with respect to the axisymmetric fit model show the positive and negative brightness modulation due to the spiral arms. These have been Fourier analyzed with respect to the azimuthal angle θ along galactocentric annuli,

$$\Delta\mu = \sum_{\rm n=0}^{10} a_{\rm n} \cos\left(n(\theta-\theta_{\rm n})\right). \qquad (3)$$

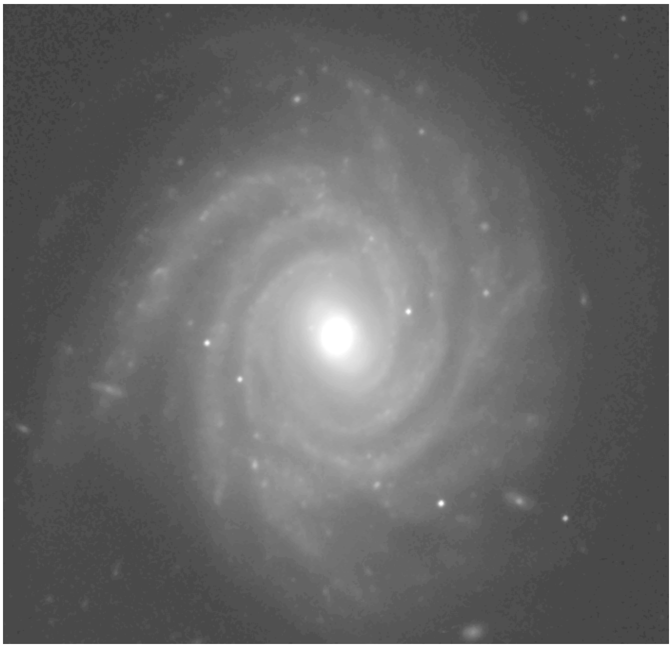

Fig. 1. I-band image of NGC 1288. North is up, east to the left, the size is $140'' \times 140''$ corresponding to 41 kpc×41 kpc.

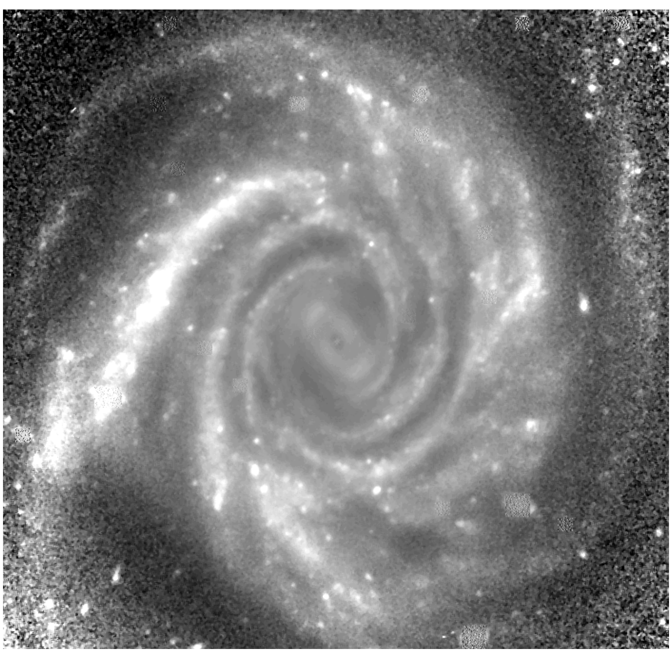

Fig. 2. Grey scale representation of the residuals of the surface brightness with respect to the axisymmetric model. The residuals have been normalized by the axisymmetric model. Same size and orientation as in Fig. 1.

The Fourier coefficients $a_1(R)$ to $a_{10}(R)$ are shown in Fig. 3 as function of galactocentric radius for each filter band as a two–dimensional contour plot. These allow a quantitative measurement of the multiplicity of the spiral arms.

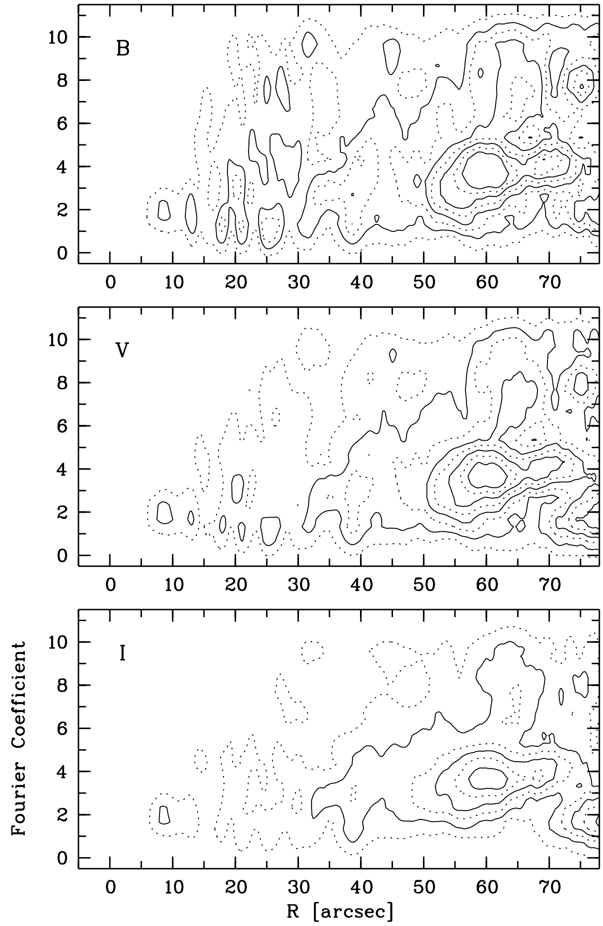

Fig. 3. Coefficients of the Fourier decomposition of the residuals of the surface brightness with respect to the axisymmetric model as function of galactocentric radius shown as a two–dimensional contour plot for each filter band. The orders of the Fourier coefficients are marked on the vertical axes of the diagrams. The Fourier coefficients have been normalized by the axisymmetric brightness component. Full contour lines correspond to the values 0.1, 0.2, 0.3, 0.4; dotted lines to 0.05, 0.15, 0.25, 0.35, respectively.

3. Density–wave theory arguments

Once the photometric parameters have been determined, a model rotation curve of the form

$$v_{\rm c}^2(R) = v_{\rm c,b}^2(R) + v_{\rm c,d}^2(R) \tag{4}$$

can be constructed, 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 Eq. (2) by

$$v_{\rm c,b}^2(R) = \frac{4\pi G \rho_{\rm b0}}{R} \int_0^R dr r^2 \left(1 + \frac{r^2}{r_{0,\rm b}^2}\right)^{-\alpha}, \tag{5}$$

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

$$v_{\rm c,d}^2(R) = 4\pi G \Sigma_{\rm d0} h x^2 \left(I_0(x)K_0(x) - I_1(x)K_1(x)\right), \tag{6}$$

where $\Sigma_{\rm d0}$ denotes 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 same mass–to–light ratio is assumed for bulge and disk, respectively. Unfortunately, the actual rotation curve of NGC 1288 is not known, but Bottinelli et al. (1986) have measured with HI observations a maximal rotation velocity of $v_{\rm c,max}$ = 468 km s^{-1}. In Fig. 4 the model rotation curve according to Eq. (4) is shown. The central surface density of the disk according to this determination is $\Sigma_{\rm d0}$ = 3500 $M_\odot$ pc^{-2}, implying an unrealistically high mass–to–light ratio of $M/L_{\rm B}$ = 24 $M_\odot/L_{\rm B\odot}$.

NGC 1288 is not a grand–design spiral. The spiral structure of such galaxies is almost certainly due to swing amplification of perturbations in the disks (Toomre 1981, 1990). If the spiral arms of NGC 1288 were rigidly rotating spiral modes of the disk, they would have to be closely connected to the bulge, because it acts as a reflector of density waves in modal theory (Bertin et al. 1998a,b, Fuchs 2000). We conclude from the models presented below that the bulge dominates the dynamics of the disk at galactocentric radii up to 0.5 kpc. In the regions adjacent to the bulge the epicyclic frequency is relatively high and the critical wave length is rather small (cf. Eqs. (7) and (8)); $\lambda_{\rm crit} \approx 6$ kpc in the models presented below. The appearance of the shapes of modes is dominated by the short wave–length solutions of the modal equations. These have typical wave lengths less than $\lambda_{\rm crit}$ (Athanassoula 1984). Thus modal theory can account only for the innermost structures in the disk, such as the small bar with an outer boundary radius of 2.6 kpc, but not for the spiral arms reaching out to galactocentric distances of 16 kpc.

Swing amplified shearing density waves can form over the disk coherent global spiral patterns with low multiplicity, which shear and eventually wrap up (Toomre 1981)[1]. Swing amplification is most effective if the circumferential wave length of the density wave is

$$\lambda = X \left(\frac{dv_{\rm c}(R)}{dR}\right) \lambda_{\rm crit} = X \left(\frac{dv_{\rm c}(R)}{dR}\right) \frac{4\pi^2 G\Sigma_{\rm d}}{\kappa^2}\,, \qquad (7)$$

where κ denotes the epicyclic frequency,

$$\kappa^2 = 2\left(\frac{v_{\rm c}}{R}\right)^2 \left(1 + \frac{d\ln v_{\rm c}}{d\ln R}\right). \qquad (8)$$

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). We apply in Eq. (7) a relation for $X(dv_{\rm c}(R)/dR)$ found by analyzing the stellardynamical equivalent of the Goldreich & Lynden-Bell sheet (Fuchs 1991). The expected number of spiral arms is given by

$$m = \frac{2\pi R}{\lambda}\,, \qquad (9)$$

and is shown in the lower panel of Fig. 4. The theoretical expectation according to a pure bulge/disk model is a two–armed spiral, which is clearly contradicted by the observation (cf. Fig. 2).

[1] In the image of NGC 1288 there is a branching of spiral arms discernible at a galactocentric radius of about 30″ spaced at 120 degrees in azimuthal angle (B. Elmegreen, private communication, cf. also Fig. 2). This may be well due to the interference of such large scale patterns.

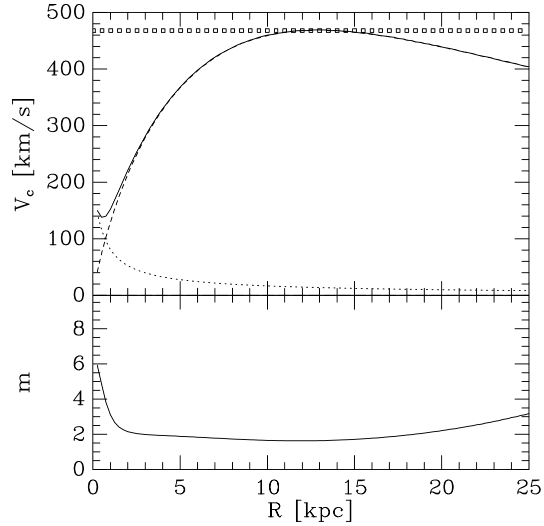

Fig. 4. Upper panel: Model rotation curve of NGC 1288. The contributions by the bulge and disk are shown as dotted and short–dashed lines, respectively. The observed maximal rotation velocity is indicated by the squared symbols. Lower panel: Expected number of spiral arms.

Since it is generally expected that galaxies are imbedded in dark matter halos, we have also considered an additional dark halo component in the construction of the model rotation curve. The dark halo is modelled by a quasi–isothermal sphere,

$$\rho_{\rm h}(r) = \rho_{\rm h0}\left(1 + \frac{r^2}{r_{\rm 0,h}^2}\right)^{-1}, \qquad (10)$$

which leads to a further term,

$$v_{\rm c,h}^2(R) = 4\pi G\rho_{\rm h0} r_{\rm 0,h}^2 \left(1 - \frac{r_{\rm 0,h}}{R}\arctan\frac{R}{r_{\rm 0,h}}\right), \qquad (11)$$

in Eq. (4). Since the rotation curve of NGC 1288 has not been measured in detail, the parameters in Eqs. (10) and (11) are not known. However, plausible models can be constructed, where the expected multiplicity of spiral arms is in accordance with the observations. In Fig. 5 we show such a model with parameters $\Sigma_{\rm d0}$ = 2000 $M_\odot$ pc^{-2}, $r_{\rm c,h}$ = 12 kpc, and $\rho_{\rm ho}$ = 0.035 $M_\odot$ pc^{-3}. The expected multiplicity of spiral arms is very similar to the observed as measured by the Fourier coefficients (cf. Fig. 3). Close to the center at $R \approx 3$ kpc (10″) we predict and observe a two–armed spiral. In the region around $R \approx 10$ kpc (35″) the geometry changes to a three–armed spiral, again in accordance with the theoretical prediction. In the domain R = 15 kpc (50″) to 20 kpc (70″) most power goes into a four–armed structure, both observationally and theoretically. This behaviour is very similar in all three colours B,V,I. However. the blue Fourier coefficients show more fine–structure due to the more pronounced effects of star formation regions and dust. Near 70″ part of the power is shifted to even higher order Fourier coefficients. This is still consistent with swing amplification theory, because the expected number of spiral arms according to Eq. (9) has been calculated from the peak amplification factor of the swing–amplification mechanism. Actually there is a broad distribution of the X parameter (cf. Fig. 1 in Fuchs 1991). The same coexistence of

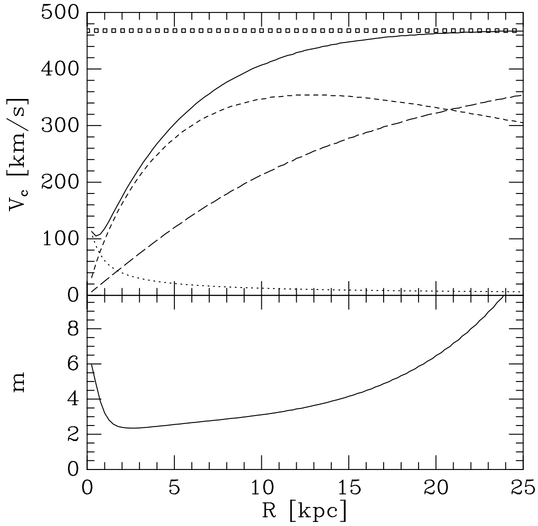

Fig. 5. Upper panel: Model rotation curve of NGC 1288, now including the contribution due to a dark matter halo (long–dashed line). Lower panel: Expected number of spiral arms.

spiral patterns with various m can be seen also in the inner parts of the disk of NGC 1288, although to a lesser degree because the amplitudes of the residuals $\Delta\mu$ are smaller there (see also Fig. 2).

Furthermore, after the introduction of a dark matter halo in the model the mass–to–light ratio is lowered to $M/L_{\rm B}$ = 14 $M_\odot/L_{\rm B\odot}$, which is more consistent with determinations in other nearby spiral galaxies.

4. Conclusions

The B–, V–, and I–images of NGC 1288 taken with FORS were of such quality that we were enabled to carry out a quantitative analysis of the morphology of the galaxy. The analysis went trough two stages: first fitting an axisymmetric bulge/disk model to the data and then Fourier analyzing the residuals, which reflect the spiral arms. In this way the galaxy could be shown in an objective, quantitative manner to be multiple armed. From the bulge/disk model we have constructed a model rotation curve, which is scaled to the terminal circular velocity measured by Bottinelli et al. (1986). The resulting mass–to–light ratio is unrealistic large. Furthermore, arguments of density wave theory of swing–amplified shearing spiral arms lead to the theoretical expectation that according to the pure disk model NGC 1288 ought be to be a two–armed spiral, which is clearly contradicted by the observations. Both conclusions change, if a dark halo is introduced to the galaxy model. The mass–to–light ratio can then be shown to be comparable to that of other galaxies. Simultaneously the theoretically expected multiplicity of the spiral arms fits exactly to the observations. We conclude form this discussion that NGC 1288 is indeed surrounded by a dark matter halo.

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