Astron. Astrophys. 352, L5–L10 (1999)

ASTRONOMY
AND
ASTROPHYSICS

Letter to the Editor

Morphological structure and colors of NGC 1232 and NGC 1288*

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Received 9 August 1999 / Accepted 23 August 1999

Abstract. Using the FORS1 focal reducer camera at the VLT UT1 (Antu) a multi-color surface photometry has been carried out for the southern Sc galaxies NGC 1232 and NGC 1288. Two-dimensional functions for the disk and the bulge were fitted to the surface-brightness distribution, yielding a high-precision disk-bulge decomposition. Nearly linear correlations for the characteristic scale parameters of disk and bulge in the different colors were found, as well as similar correlations for the central surface brightness of the disk and the effective surface brightness of the bulge. This seems to indicate that there exist connections between disk and bulge properties in spiral galaxies and their stellar density and population distributions.

Key words: galaxies: individual: NGC 1232; NGC 1288 – galaxies: fundamental parameters – galaxies: photometry – galaxies: spiral – galaxies: structure

1. Introduction

NGC 1232 is a bright southern Sc spiral galaxy ($B_{\rm T} = 10.52$, RC3, de Vaucouleurs et al. 1991) in nearly face-on position. It has a multiple-arm structure (Elmegreen et al. 1992) with numerous patches of star formation. The inner arms are characterized by distinct chains of star formation regions, especially detectable in U and B (cf Fig. 1). The radial velocity relative to th 3 K background is $v_{3\,{\rm K}} = 1519\,{\rm km\,s^{-1}}$, indicating a distance of about $D = 20$ Mpc.

The Sc spiral NGC 1288 is also nearly face on. It is somewhat fainter ($B_{\rm T} = 12.78$, RC3). The distance is larger. From $v_{3\,{\rm K}} = 4405\,{\rm km\,s^{-1}}$ we assume $D = 60$ Mpc.

In this paper we investigate the surface brightness distribution of these galaxies in U, B, V, R, I (NGC 1232), resp. B, V, I (NGC 1288), using images obtained during the comissioning of FORS1 at the ESO VLT UT1 (Antu). Due to the good spatial resolution and the large field these images are particularly well suited for morphological studies of fine details as well as of the overall structure in the different colors.

Sect. 2 and Sect. 3 give a short description of the observations and basic data reductions. Sect. 4 shortly describes a new method of a two-dimensional fit to the surface brightness and disk-bulge decomposition. Sect. 5 and Sect. 6 present the resulting structural parameters and some important correlations. In Sect. 7 we discuss the results and present some conclusions.

2. Observations

NGC 1232 was observed on Sept. 21, 1998 during the comissioning 1 phase of FORS1 (Focal Reducer Spectrograph, cf. Appenzeller et al. 1997, 1998) at the ESO VLT1 (Antu). Broad band imaging in the Bessel U, B, V, R, I filters was performed with exposure times of 600, 360, 180, 150, 180 sec respectively. The seeing was 0.7 arcsec FWHM in all filters. The detector was a thinned Tektronix TK2048EB4-1 CCD with 2048×2046 pixels and $24 \times 24\,\mu$ pixel size. In the standard resolution imaging mode FORS1 has a resolution of 0.2 arcsec/pix. Thus the field was 6.83×6.83 arcmin which is just adequate for NGC 1232.

NGC 1288 was observed on Sept. 16, 1998 with the same equipment. Broad band imaging in the Bessel B, V, I filters was performed with exposure times of 360, 180, 180 sec, respectively. The seeing during these exposures was 0.7 to 0.8 arcsec FWHM.

3. Standard data reduction and results

The data reduction consisted of the usual procedures, i.e. bias subtraction and flat field division. Due to the condensation of some contamination from the dewar on the chip surface the flat field images were changing progressively with time. A mean flat field was constructed from many twilight flats which allowed to obtain a flat sky background. The frames were filtered using a 3×3 median filter. The photometric calibration was carried

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

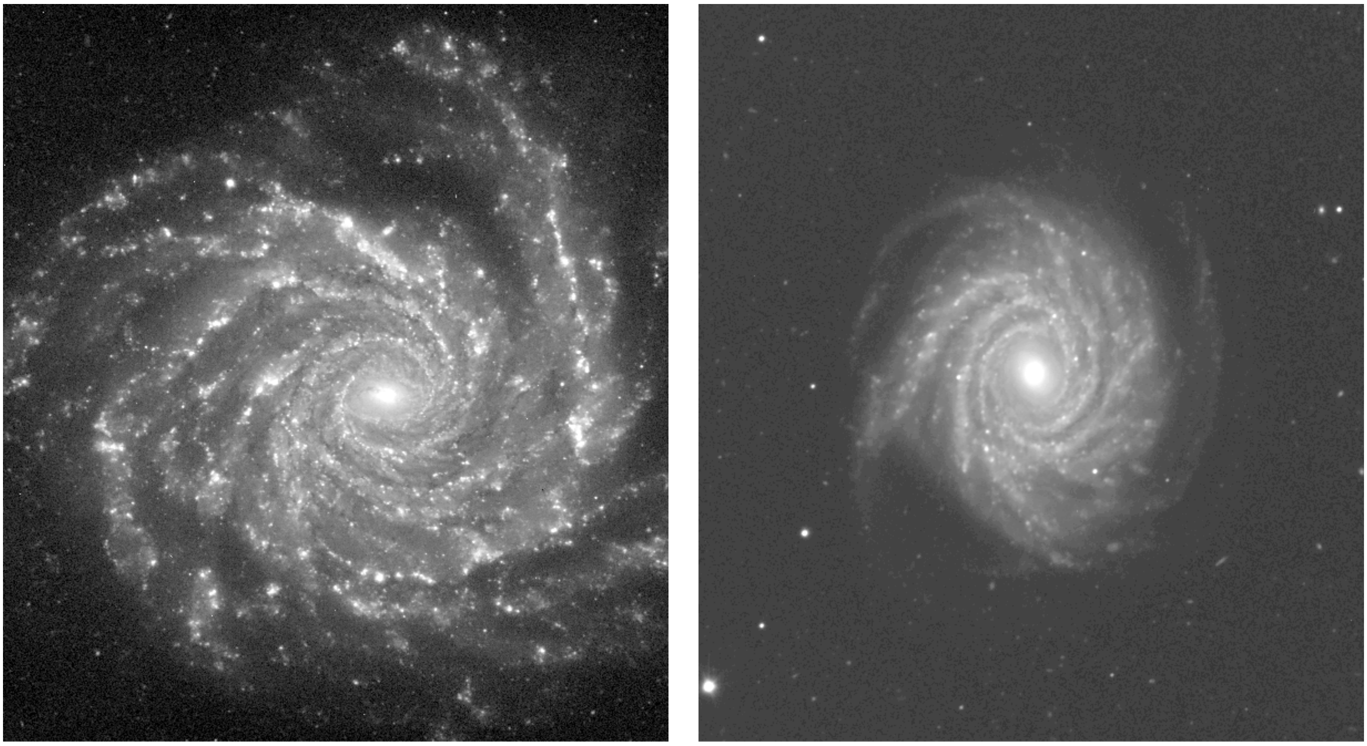

Fig. 1. Left: B-filter image of NGC 1232. The size is 6×6.7 arcmin. North is up, east to the left. Right: NGC 1288 in B-filter, the size is 3×3.35 arcmin.

out by using corresponding exposures of photometric standard stars. The images of NGC 1232 were extracted to 1800×2000 pixels to cut off the companion galaxy in the SW corner. For NGC 1288 a subframe of the central 1000×1000 pixels turned out to be sufficient. Fig. 1 shows the reduced B-filter images of NCC 1232 and NGC 1288.

4. Fit of the surface brightness distribution

The derivation of the basic structural parameters of spiral galaxies by fitting composite models to the surface brightness (SB) distribution has a long tradition (e.g. Freeman 1970, Boroson 1981, Andredakis & Sanders 1994). In recent papers it was shown that a two-dimensional fit to the whole galaxy image gives more realistic results compared to the usual fit of a disk- and bulge-function to a one-dimensional surface brightness profile (Byun & Freeman 1995, de Jong 1996a). Here we apply a new method for two-dimensional fits which uses a three-parameter fit function for the bulge (Möllenhoff, 1999a).

In principle the procedure consisted of the following steps: The observed flux distribution was fitted simultaneously by two-dimensional surface brightness (SB) functions for disk and bulge. For the radial flux distribution flux of the inclined disk we assumed the exponential law

$$F_{\rm d}(R) = I_{\rm d}\ \exp(-R/R_{\rm d}). \qquad (1)$$

where $I_{\rm d}$ is the central flux density and $R_{\rm d}$ the radial scale length. No outer truncation radius was used. The disk was assumed to be axisymmetric. The inclination then leads to the elliptical geometry

$$R^2 = (x\cos\phi_{\rm d} + y\sin\phi_{\rm d})^2/{Q_{\rm d}}^2 + (y\cos\phi_{\rm d} - x\sin\phi_{\rm d})^2 \qquad (2)$$

where $\phi_{\rm d}$ is the position angle (P.A.) of the major axis measured anticlockwise from north, and $Q_{\rm d} = b/a$ is the axis ratio. Hence there are 4 free fit parameters for the disk.

As shown in Möllenhoff (1999b), it is not possible to obtain meaningful bulge fits using an exponential function with a fixed power of the radius (e.g. $1/4$ for the de Vaucouleurs profile). Therefore, it is necessary to treat the exponent of R as a third structural parameter for the bulge. A suitable parametrization is the Sérsic radial density law (Sérsic 1968) with the parameters $I_{\rm s}, R_{\rm s}$, and $1/n$ (see also Andredakis et al. 1995).

$$F_{\rm b}(r) = I_{\rm s}\ \exp[-(R/R_{\rm s})^{1/n}] \qquad (3)$$

This relation can also be expressed in the form of a generalized de Vaucouleurs profile:

$$F_{\rm b}(r) = I_{\rm b}\ \exp(-b_e[(R/R_{\rm b})^{\beta} - 1]) \qquad (4)$$

where the real number exponent $\beta = 1/n$ determines the slope of the projected bulge SB distribution. With

$$b_{\rm e} = 1.9986/\beta - 0.327, \qquad (5)$$

$R_{\rm b}$ is the half-light or effective radius and $I_{\rm b}$ is the flux at $R_{\rm b}$ (Caon et al. 1993). Using a similar expression as Eq. (2) for the radius R, we obtain the position angle $\phi_{\rm b}$ and the ellipticity $Q_{\rm b}$ as 4th and 5th free fit parameters for the bulge. Fitting the

Table 1. Structural parameters of NGC 1232 and NGC1288. The distances to NGC 1232 and NGC 1288 were assumed to 20 Mpc and 60 Mpc, respectively.

NGC	Filt	$SB_{\rm cd}$ mag/sas	$R_{\rm d}$ arcsec	$R_{\rm d}$ kpc	$\phi_{\rm d}$ deg	$Q_{\rm d}$	$SB_{\rm cb}$ mag/sas	$R_{\rm b}$ arcsec	$R_{\rm b}$ kpc	$\phi_{\rm b}$ deg	$Q_{\rm b}$	β	$L_{\rm tot}$ mag	$L_{\rm disk}$ mag	$L_{\rm bulge}$ mag	Bu/Di −Ratio
1232	U	21.74	81.65	7.92	91.6	0.846	21.85	5.91	0.57	89.42	0.675	0.985	10.36	10.37	15.71	0.007
	B	21.57	71.40	6.92	89.8	0.873	21.74	8.07	0.78	87.13	0.625	0.750	10.44	10.46	14.89	0.017
	V	20.79	60.95	5.91	91.8	0.891	21.05	10.52	1.02	84.51	0.603	0.613	09.95	09.99	13.55	0.038
	R	20.19	56.69	5.50	91.0	0.913	20.52	11.35	1.10	83.50	0.587	0.566	09.48	09.53	12.85	0.047
	I	19.55	53.62	5.20	89.7	0.921	19.97	12.04	1.17	82.22	0.585	0.546	08.94	08.99	12.16	0.054
1288	B	21.48	24.99	7.27	4.2	0.817	21.03	2.33	0.68	0.18	0.867	0.581	12.93	12.96	16.63	0.034
	V	20.64	22.41	6.52	4.5	0.815	20.54	3.24	0.94	4.64	0.849	0.446	12.14	12.21	15.17	0.066
	I	19.43	20.85	6.06	4.5	0.819	19.73	4.05	1.18	8.88	0.841	0.380	11.03	11.12	13.78	0.086

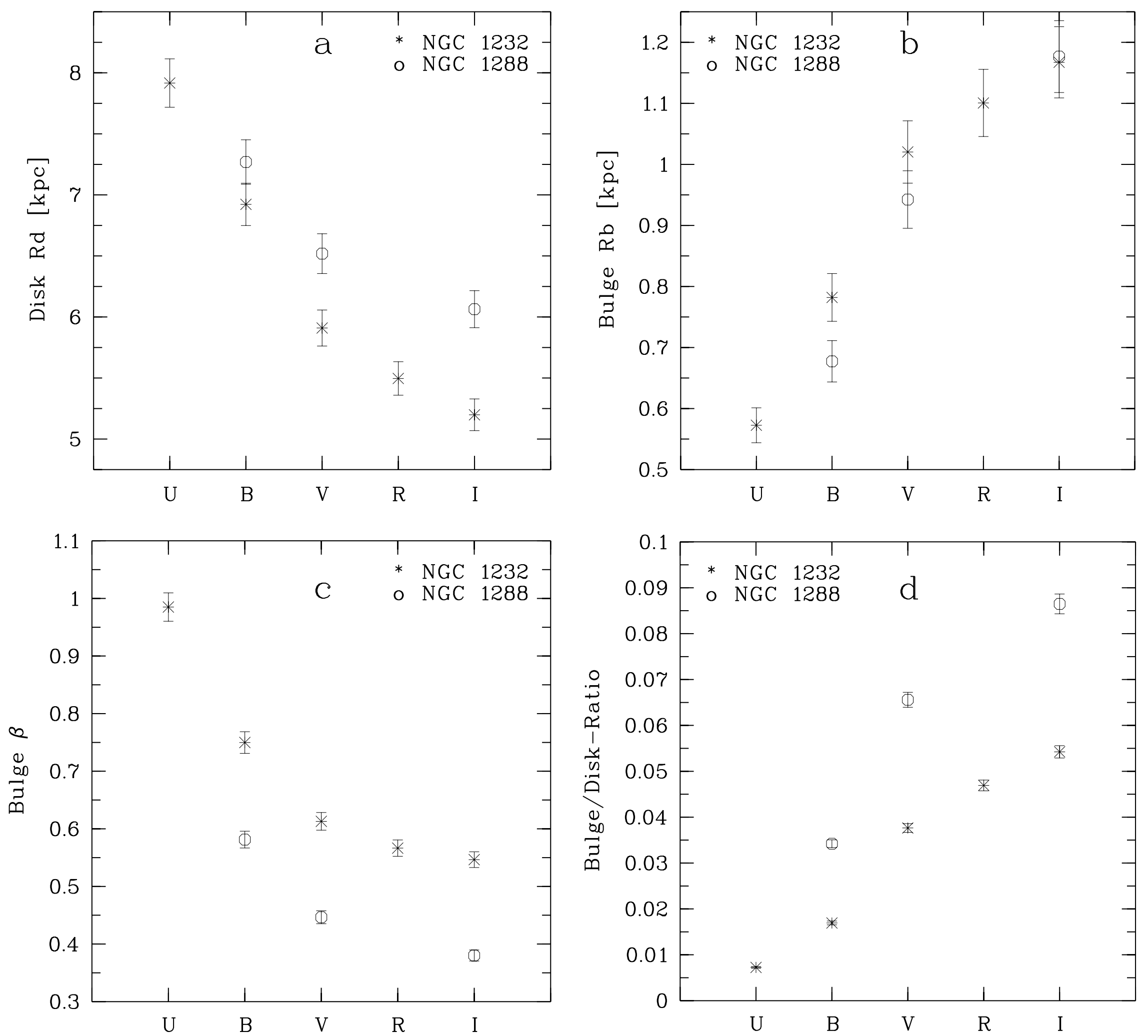

Fig. 2a–d. The linear disk scale lengths of NGC 1232 and NGC 1288 decrease with colors U, B, V, R, I resp. B, V, I **a**, in contrast to that the bulge effective radii increase from blue to red colors **b**. The β-exponents of the bulges of these galaxies decrease with the colors U, B, V, R, I **c**; the bulge-to-disk ratios increase, i.e. the bulges are more luminous in red colors **d**. The errors of the parameters are mainly determined by the accuracy of the sky subtraction.

total flux $F = F_d + F_b$ simultaneously to the observed two-dimensional SB distribution results in a nonlinear system of equations for the $4 + 5 = 9$ free parameters which was solved using the *Levenberg-Marquardt*-method. Further details of the method can be found in Möllenhoff (1999b).

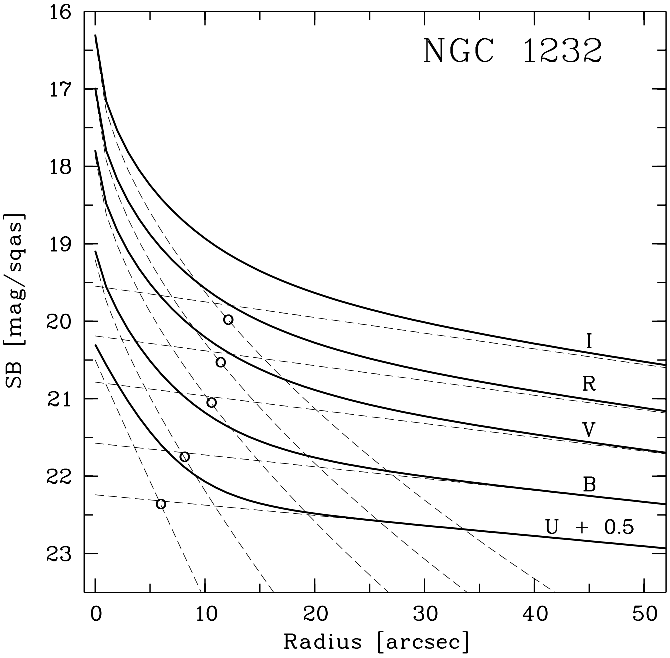

Fig. 3. Surface-brightness profiles of NGC 1232 const/ructed from the parameters of the two-dimensional fit. The dotted lines are the profiles of disk resp. bulge, the full line is the sum. The slope of the disks decreases slightly from red to blue, corresponding to the increasing scale length R_d. In red colors the bulges are larger and flatter compared to blue colors. The corresponding effective radii in the bulge profiles are marked by a circle. Only the inner 50 arcsec are shown.

It is necessary to consider the effects of atmospheric seeing on the galaxy image, especially for the bulge fit. The point spread function (PSF) was approximated by a 2-dimensional Gaussian profile and was convolved with the total fit function during each iteration step.

5. Results of the fit

The resulting fit parameters as well as some other quantities for NGC 1232 (U, B, V, R, I) and NGC 1288 (B, V, I) are given in Table 1.

Fig. 2 presents the variations of different structural parameters of the two galaxies with color. As shown by Fig. 2a the disk scale length R_d decreases monotonically from blue to red. The increase of the disk scale length for blue colors had already been observed in one-dimensional SB fits by Prieto et al. (1992) and Pompei & Natali (1997). The phenomenon of the increasing portion of blue color in the outer disk region was discussed more thoroughly by de Jong (1996c) and was interpreted as the result of an increasingly younger stellar population in the outer disk. Dust extinction and dust reddening are probably not responsible for this effect (Byun et al. 1994, Xilouris et al. 1999).

Fig. 2b shows the variation of the bulge effective radius R_b with color for the two galaxies. R_b behaves inversely compared to the disk: it increases for the red colors, i.e. the bulge is more extended in the red.

Fig. 2c shows the variation of the bulge slope parameter β with color for the two galaxies. β decreases monotonically from blue to red: In the case of NGC 1232 from $\beta \approx 0.98$ (for U) to $\beta \approx 0.54$ (for I). For NGC 1288 the β-values are systematically lower ($\beta \approx 0.58$ for B and $\beta \approx 0.38$ for I). For both galaxies the curvature of the bulge profile is stronger in the red colours. This variation of β with color demonstrates again that it is not adequate to fit bulges with one single fixed β value.

Fig. 2d shows the bulge-to-disk ratio as a function of the color. There is a strong increase of B/D from blue to red colors.

The main contributions for errors in the fit results are due to the limited accuracies of the sky subtractions ($\approx$ 1%) and of the determination of the seeing point spread function (PSF; $\approx$ 3%). The resulting errors in the structural parameters of the galaxies were determined by test calculations with corresponding offsets in sky subtraction and PSF. We obtain $\approx$ 2.5% error for the disk parameters and and for β, and $\approx$ 5% error for the bulge parameters. The corresponding error bars are drawn in Fig. 2.

Fig. 3 shows the one-dimensional SB profiles for NGC 1232 in U, B, V, R, I as they are derived from the two-dimensional fit for the structural parameters. For easier visibility, the U-curve is shifted towards 0.5 mag fainter. The trend of an increasing and flatter disk for bluer colors can easily be seen. Correspondingly, the bulge increases and gets flatter towards redder colors. Due to the decreasing β, the red bulge profiles in Fig. 3 show a stronger curvature than the blue ones. The profiles for NGC 1288 show very similar properties.

6. Correlations between the structural parameters

Fig. 4 (left) shows the correlations between the disk scale length R_d and the bulge effective (half-light) radius R_b for the different colors. It is remarkable that there exists a nearly linear anticorrelation of these quantities for both galaxies, although with a slightly different slope. We have plotted here the linear scales in kpc. It is important to remember that the observed behaviour is independent of distance. A changing distance just shifts the curves in the diagram along the line with slope 1.

Fig. 4 (right) shows the correlations between the central surface brightness of the disk (SB_cd) and the surface brightness of the bulge at the effective or half-light radius (SB_cb) for the different colors of NGC 1232 and NGC 1288. Again we find nearly perfect linear trends with a different slope for each galaxy. It should be remembered that the effective radius of the bulge changes with color (Fig. 2b). Therefore SB_cb is not at the same radius for the different colors, in contrast to the central surface brightness SB_cd of the disk. The corresponding effective radii of the bulges are marked in their surface brightness curves in Fig. 3. The SB relations in Fig. 4 (right) are independent from the distances of the galaxies.

7. Discussion and conclusion

We have analysed deep high resolution images of NGC 1232 and NGC 1288 in several colors. A deconvolution of the surface brightness distribution into a disk and a bulge yields structural

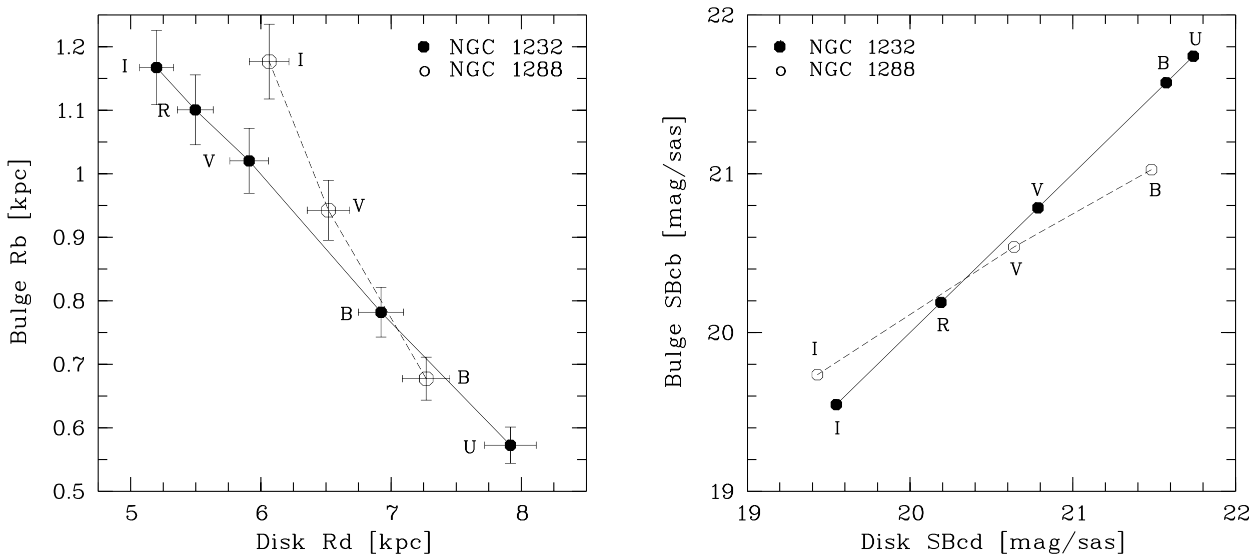

Fig. 4. Left: The comparison between the characteristic scale lengths of bulge and disk (R_b and R_d) for the different colors of both galaxies shows nearly linear anticorrelations. **Right:** The correlations between the central surface brightness of the disk and the surface brightness of the bulge at the effective radius show good linear trends. The corresponding colors are marked. The errors are of similar size as the symbols

parameters of the galaxies which vary systematically with the colors. We use a new improved two-dimensional fit method for this purpose. It considers the whole structure of the galaxy and determines the most adequate fit function for disk and bulge simultaneously. No a-priori separation of a disk-region or a bulge-region is necessary. Therefore, this fit method seems well suited to describe quantitatively the overall distribution of the stellar populations.

As usual, the disk is described mainly by the two parameters central surface brightness I_d and disk scale length R_d. The main improvement of our two-dimensional fit is the treatment of the bulge region. The bulge ellipticity and position angle are independent parameters, normally different from those of the disk. Only by using two-dimensional functions triaxial bulges can be described at all. A detailed study of the residual differences between galaxies and their fit models show that it is necessary to use three parameters in order to describe bulges adequately (Möllenhoff, 1999b). These parameters are the effective radius R_b, the surface brightness I_b at R_b, and the slope exponent β. A fixed bulge exponent (e.g. a de Vaucouleurs $r^{1/4}$ or an exponential profile) does not give a realistic fit. The convolution of the fit function with an accurately determined seeing PSF is important as well.

A systematic trend of an increasing β with Hubble type was observed if different galaxies are studied in one color (Andredakis et al. 1995, Möllenhoff, 1999a). Here we have the new result that for a single galaxy β varies with color. This color dependence is very similar for the two Sc spirals considered here, β decreases from blue to red colors (Fig. 2c).

NGC 1232 was studied in U, B, V, R, I already by Pompei & Natali (1997). They constructed surface brightness profiles by integration over circular rings. In a second step they fitted an exponential disk, subtracted the disk, and fitted then a de Vaucouleurs-bulge ($\beta = 1/4$ fixed). Their results show the same general trend: the disk scale lengths decreased from U to I, while the bulge effective radii increased. However, their values of R_d and R_b are smaller by about a factor of 0.7 than our numbers. This discrepancy is probably due to the use of our improved method.

The bulge of NGC 1232 shows in projection a smaller ellipticity than the disk, and the corresponding position angles are very different (cf. Table 1). Given the plausible assumption that the main planes of symmetry (or the rotation axes) of disk and bulge coincide, the bulge of NGC 1232 has to be triaxial.

The disk-bulge deconvolution and the determination of the structural parameters for NGC 1288 are new. Hence no comparison with literature values is possible. In general this galaxy is rather similar to NGC 1232.

Comparing the results between the different colors for the two galaxies, we find clear anticorrelations between the disk scale length R_d and the bulge effective radius R_b, and linear correlations between their characteristic surface brightness values SB_cd and SB_cb. Such correlations have not yet been published before.

It has been established from several observations that the scale lengths of the disks of spiral galaxies are larger in the blue than in the red colors. This has been explained by dust extinction with a similar exponential density distribution as that of the stars (e.g. Evans 1994, Beckman et al. 1996). However, this explanation is still controversial. Other authors estimate the optical depth of spiral galaxies as too small for being responsible for this effect (Byun et al. 1994, Xilouris et al. 1999). An alternative and more plausible explanation is a radial variation of stellar population, i.e. of age and/or metallicity (e.g. Rix & Rieke 1993, de Jong 1996c).

The observed correlations indicate a strong connection between stellar density structure and population content in spiral galaxies. Independent observational support for correlations between the bulge- and the disk-population is given in Peletier & Balcells (1996). They found a strong similarity between the old underlying populations in the disk and the bulge. Courteau et al. (1996) discovered close relations between the scale lengths of disks and bulges if both components are fitted by exponential functions. De Jong found for his sample of 86 spirals a correlation between bulge and disk scale lengths, suggesting that the formation of the bulge and the disk is coupled (de Jong 1996b). These observations show only certain aspects of such a connection, but they point to a much closer relationship between bulges and disks of spiral galaxies than the classical paradigm would lead us to expect.

There exist some theoretical studies proposing a common formation or close connections between disk and bulge: Wyse (1998) discusses the phase-space constraints for a scenario, in which the stellar bulges form from stellar disks. Vine & Sigurdsson (1998) follow the evolution of high density disks and their partial transformation into bulges using an N-body code. The observations presented here provide strong support for such scenarios.

Acknowledgements. We are grateful for discussions with R. Bender (München) and B. Fuchs (Heidelberg). Part of this work was supported by the *Deutsche Forschungsgemeinschaft, DFG*, SFB 439.

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