H I STUDIES OF THE SCULPTOR GROUP GALAXIES. VIII. THE BACKGROUND GALAXIES: NGC 24 AND NGC 45

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ABSTRACT

In order to complete our H I survey of galaxies in the Sculptor group area, Very Large Array observations of NGC 24 and NGC 45 are presented. These two galaxies of similar magnitude, $M_B \sim -17.4$, lie in the background of the Sculptor group and are low surface brightness galaxies, especially NGC 45. The H I distribution and kinematics are regular for NGC 24, while NGC 45 exhibits a kinematical twist of its major axis. A tilted-ring model shows that the position angle of the major axis changes by $\sim 25^\circ$. A best-fit model of their mass distributions gives mass-to-light ratios for the stellar disk of 2.5 and 5.2 for NGC 24 and NGC 45, respectively. These values are higher than those expected from stellar population synthesis models. Despite the large dark matter contribution, the galaxy mass is still dominated by the stellar component in their very inner regions. These high mass-to-light ratios are typical of what is seen in low surface brightness galaxies and may indicate that, in those galaxies, disks are far from the maximum disk case. The halo parameters derived from the best-fit models are thus lower limits.

Key words: galaxies: fundamental parameters (masses) — galaxies: halos — galaxies: individual (NGC 24, NGC 45) — galaxies: kinematics and dynamics — galaxies: structure

1. INTRODUCTION

At the beginning of the 1990s a series of papers was started on the H I properties of the Sculptor group galaxies (Puche & Carignan 1988, 1991; Carignan & Puche 1990a, 1990b; Puche et al. 1990, 1991a, 1991b). Since the Sculptor galaxies are all late-type spiral galaxies with very little or no bulge, they are ideal candidates for determining the basic dark halo parameters (Carignan & Freeman 1985). Their simple disk plus halo structure makes it easier to identify the contribution of each component to the rotation curve. Also, since the H I distribution of late-type spiral galaxies is usually extended (Huchtmeier et al. 1980), it is possible to measure their rotation curve out to many disk scale lengths, an essential condition to tie down the halo parameters (Lake & Feinswog 1989).

As described in Puche & Carignan (1988), the Sculptor group, the nearest group of galaxies to the Local Group, covers an area of $\sim 20^\circ$ on the sky. In this area, besides the five main members studied so far (NGC 55, NGC 247, NGC 253, NGC 300, and NGC 7793), two more galaxies, NGC 24 and NGC 45 (Fig. 1), fall in the same region and have similar sizes and degree of resolution, as do ~ 20 known dwarf galaxies (Côté et al. 1997, 2000). However, when looking at the estimated distances, a mean distance of 2.4 ± 0.6 Mpc is found for the main members (de Vaucouleurs 1978) but 6.8 Mpc (7σ) and 5.9 Mpc (6σ) for NGC 24 and NGC 45, respectively (based on a Hubble constant of $75 \text{ km s}^{-1} \text{ Mpc}^{-1}$; Tully 1988). Moreover, when doing dynamical mass estimates of the group, any combination of the main members consistently gives $\sim 3 \times 10^{12} M_\odot$ for the group, while including NGC 24 and NGC 45 makes the estimate jump to $\sim 3 \times 10^{13} M_\odot$, clearly too large for a loose group like Sculptor. All this strongly suggests that NGC 24 and NGC 45 are not members of the group but background objects.

Even if they are not members of the Sculptor group, it was decided to study them because they belong to a very interesting subgroup of galaxies called the low surface brightness (LSB) spiral galaxies, especially NGC 45. The kinematical study of LSB galaxies currently feeds the “cusp-core controversy,” (e.g., Swaters et al. 2003; Hayashi et al. 2004; de Blok 2005 and references therein). One of the many important questions that is brought to the forefront from the numerous studies of this type of object and that motivates part of the present work is whether or not LSB galaxies (and more generally low-mass late-type spiral galaxies) can possibly form a distinct class in the Hubble sequence. The hypothesis emanating from studies on LSB galaxies is that they belong to the spiral class morphologically, but they look more like the dwarf irregular class dynamically, since they are dominated at all radii by their dark halo (Jobin & Carignan 1990; Côté et al. 1991; Martimbeau et al. 1994).

Moreover, a study of optical rotation curves of spiral galaxies (Buchhorn 1992) showed convincingly that the optical rotation curves in the inner parts of these galaxies give $(M/L_B)_*$ ratios that are very high. The most likely explanation for this effect is that the dark matter component contributes a large fraction of the gravitational field even in the inner regions of LSB galaxies (de Blok & Bosma 2002). Verheijen (1999) and Verheijen & Tully (1999) have shown convincingly the clear dichotomy between the rotation curves of high surface brightness galaxies, which are most of the time close to the maximum disk situation, and those of LSB galaxies, which are dominated at all radii by the dark matter component. Thus, in terms of their mass distribution, LSB galaxies appear to be more closely related to dwarf irregular galaxies (e.g., DDO 154; Carignan & Freeman 1988; Carignan & Beaulieu 1989), in which the luminous component is known to make a negligible contribution to the gravitational field everywhere in the disk, than to massive spiral galaxies (e.g., NGC 6946; Carignan et al. 1990), in which the luminous disk is the main contributor in the inner regions and the dark component only contributes significantly in the outer parts.

In order to get a better understanding of the mass distribution in NGC 24 and NGC 45, both optical and 21 cm radio observations were obtained and are presented in § 2. In § 3 the luminosity profiles and the optical properties are discussed. After studying

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FIG. 1.—DSS blue images of NGC 24 (*left*) and NGC 45 (*right*).

the H I content and its distribution in § 4, § 5 concentrates on the velocity field of these systems and presents their rotation curves. In § 6 the data are analyzed in terms of a two-component model: a luminous (stellar plus gaseous) disk and a dark halo, represented by an isothermal sphere potential. Finally, the discussion in § 7 is followed by a summary of the results in § 8.

2. OBSERVATIONS

2.1. Optical Data

The surface photometry of NGC 24 was obtained from a set of observations in the *I* band using a 1024×1024 Thompson CCD, with the f/1 focal reducer at the prime focus of the Anglo-Australian Telescope 3.9 m. The $19 \mu\text{m}$ pixels resulted in a resolution of $0''.98 \text{ pixel}^{-1}$ for a total field of $16''.7 \times 16''.7$. The adopted mean extinction was 0.085 per air mass in the *I* band. The data were obtained in 1990 September, with integration times of 20 and 5 s. After the images were bias subtracted and flat-fielded using dark sky flats, the foreground overexposed stars were removed. Pixels within a circular region were deleted and replaced by a two-dimensional surface function evaluated from the pixels lying in a surrounding background annulus. Afterward, the sky

previously evaluated by averaging the signal of many regions depleted of stars was subtracted from the galaxy image.

2.2. Radio Data

In order to get the kinematical information needed, high-sensitivity low-resolution H I line observations were obtained with the Very Large Array (VLA).⁴ They consist of 6 hr observations for each galaxy (5 hr on source, 1 hr on calibrators) made in 1992 June. In order to get a better *u-v* plane coverage, the hybrid DnC configuration, with larger antenna spacings in the north arm, was selected, since NGC 24 ($\delta \simeq -25^\circ$) and NGC 45 ($\delta \simeq -23^\circ$) are at low declinations. The candidates have been observed with a total bandwidth of 1.56 MHz divided in 128 channels and using online Hanning smoothing. This gives a channel separation of 12.2 kHz, corresponding to 2.5 km s^{-1} . The parameters of the synthesis observations can be found in Tables 1 and 2. No attempt to correct for the beam-smearing effect is done in this article.

⁴ The VLA is operated by the National Radio Astronomy Observatory (NRAO), which is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

TABLE 1
PARAMETERS OF THE VLA OBSERVATIONS FOR NGC 24

Parameter	Value
Date of observation.....	1992 Jun 14
Time on source	5 hr
Field center (B1950.0)	$00^{\text{h}}07^{\text{m}}24^{\text{s}}.0, -25^\circ 14'30''.0$
Primary beam at half power (FWHM).....	$32'$
FWHM of synthesized beam.....	$40'' \times 40''$
Total bandwidth	1.56 MHz
Central velocity (heliocentric).....	550 km s^{-1}
Central frequency.....	1417.2489 MHz
Number of channels.....	128
Channel separation.....	12.2 kHz
Velocity resolution.....	2.5 km s^{-1}
rms noise in channel maps.....	$2.4 \text{ mJy beam}^{-1}$
Conversion factor, equivalent 1 mJy beam^{-1} area (low resolution) $40'' \times 40''$	0.38 K
Map gridding	$10'' \times 10''$; natural weighting, no taper
Flux calibrator.....	0134+329

TABLE 2
PARAMETERS OF THE VLA OBSERVATIONS FOR NGC 45

Parameter	Value
Date of observation.....	1992 Jun 13
Time on source.....	5 hr
Field center (B1950.0).....	00 ^h 11 ^m 30 ^s .0, −23°27′60″.0
Primary beam at half power (FWHM).....	32′
FWHM of synthesized beam.....	42″ × 42″
Total bandwidth.....	1.56 MHz
Central velocity (heliocentric).....	470 km s ^{−1}
Central frequency.....	1418.3115 MHz
Number of channels.....	128
Channel separation.....	12.2 kHz
Velocity resolution.....	2.5 km s ^{−1}
rms noise in channel maps.....	1.6 mJy beam ^{−1}
Conversion factor, equivalent 1 mJy beam ^{−1} area (low resolution) 42″ × 42″.....	0.34 K
Map gridding.....	10″ × 10″, natural weighting, no taper
Flux calibrator.....	0134+329

First, the u - v data sets were carefully examined to detect and reject bad points due to interference or crosstalk between antennae. Antennae that were shadowed by another antenna during the observations were flagged bad for the shadowing period. The data were then calibrated using the standard VLA calibration procedure. The flux scale was obtained using the continuum source 0134+329. A bandpass calibration was also applied. The reduction was done using the NRAO software package AIPS at the VLA and at the Université de Montréal.

First, by creating and inspecting a preliminary series of channel maps, the channels containing only continuum radiation were identified. Next, those channels, free of emission lines, were averaged in the u - v plane to represent the continuum radiation and subtracted from all the channels. Finally, the channel maps were produced and cleaned simultaneously via a Fourier transform with natural weighting and no taper. The pixel size was 10″ for both systems, and the original beams were convolved by circular beams of 40″ × 40″ for NGC 24 and 42″ × 42″ for NGC 45. This was done to make sure that all the structures that were observed were not due to the original slightly elongated beam shape. The resulting maps had an rms noise of 2.4 and 1.6 mJy beam^{−1} for NGC 24 and NGC 45, respectively.

3. OPTICAL PROPERTIES

3.1. NGC 24

A study of the I -band isophotes shows that the intrinsic axis ratio varies from 0.5 near the center to 0.26 at the last measured

isophote. The mean photometric parameters computed within the radius range 1′.5–3′.0 are $i = 78^\circ \pm 5^\circ$ ($b/a = 0.26$) and P.A. = $225^\circ \pm 5^\circ$.

The elliptically averaged luminosity profile in the I -band, illustrated in Figure 2 and listed in Table 3, was obtained using the *ellipse* task in IRAF.⁵ In the very inner parts ($R \leq 50''$) the profile shows a decrease, probably due to internal absorption, while in the outer parts it reveals a typical exponential decline. An exponential fit to the I luminosity profile ($80'' \leq R \leq 180''$) yields an extrapolated central surface brightness of 19.12 mag arcsec^{−2}, which, when corrected for I Galactic extinction and inclination, gives $I(0)_c = 20.67$ mag arcsec^{−2}. A Galactic extinction $A_I = A_B/2.5 = 0.024$ (Draine 1989) was used, where $A_B = 0.06$, according to de Vaucouleurs et al. (1991, hereafter RC3). The derived exponential scale length is $\alpha^{-1} \sim 43''$, which corresponds to ~ 1.42 kpc at 6.8 Mpc.

When transformed to the B band ($\mu_B = \mu_I + 1.452$ for the Sc morphological type, from Carignan [1983]),⁶ this finally gives $B_c(0) = 22.12 \pm 0.3$ mag arcsec^{−2}, which is faint relative to the Freeman canonical value of 21.65 ± 0.30 for normal spiral galaxies (Freeman 1970). The central surface brightness of NGC 24 lies in the range of $22.07 \text{ mag} < B_c(0) < 23.70 \text{ mag}$, as defined

⁵ IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the NSF.

⁶ This was derived using mean spectral energy distributions (Coleman et al. 1980) for the different morphological types convolved with the $UBVRI$ filter responses (Bessell 1979).

Fig. 2.— I -band luminosity profile of NGC 24 (left) and B -band luminosity profile (Romanishin et al. 1983) of NGC 45 (right).

TABLE 3
I-BAND LUMINOSITY PROFILE OF NGC 24

Radius (arcsec)	μ_I (mag arcsec ⁻²)
1.96.....	18.54
2.37.....	18.57
2.87.....	18.59
3.48.....	18.61
4.21.....	18.63
5.09.....	18.64
6.15.....	18.69
7.45.....	18.83
9.01.....	18.99
10.90.....	19.11
13.19.....	19.19
15.96.....	19.26
19.31.....	19.33
23.37.....	19.42
28.27.....	19.48
34.21.....	19.61
41.39.....	19.87
50.09.....	20.14
60.60.....	20.58
73.33.....	21.11
88.73.....	21.38
107.4.....	21.95
129.9.....	22.41
157.2.....	23.11
190.2.....	24.22

by Romanishin et al. (1983) for their LSB sample, but is at the limit (within the errors) between low surface brightness objects and normal galaxies. One notices here that, contrary to NGC 45, which is a genuine LSB galaxy (Romanishin et al. [1983]; see § 3.2) with anemic spiral arms and no evident bulge (Fig. 1), the morphological properties of NGC 24 (presence of distinct spiral arms and a small bulge) are comparable with those of high surface brightness late-type spiral galaxies.

Integrating the B luminosity profile gives a total apparent magnitude $B_T = 12.13$, which is in good agreement with the value of 12.10 given by Sandage & Tammann (1987) and the value of 12.19 in RC3. When corrected for internal absorption ($A_i/2.5 = 0.38$ [Draine 1989], where $A_i = 0.95$ from RC3) it gives $B_T^{0,i} = 11.75$. At the distance of 6.8 Mpc the corrected absolute magnitude is $M_T^{0,i}(B) = -17.41$. The corrected absolute magnitude corresponds to a total blue luminosity of $1.4 \times 10^9 L_{B\odot}$. Table 4 summarizes the optical parameters of NGC 24.

3.2. NGC 45

The photometric inclination is $55^\circ \pm 5^\circ$, and the position angle of the major axis is $145^\circ \pm 5^\circ$ (Puche & Carignan 1988). A B -band surface brightness profile is used for NGC 45, as derived in Romanishin et al. (1983). We refer the reader to this article for the observational information on these data. The B -band profile is shown in Figure 2 (*right*) and listed in Table 5. Romanishin et al. (1983) gave an extrapolated central surface brightness $B_c(0) = 22.51 \pm 0.46$ mag arcsec⁻² and a scale length of $\sim 77''$. This value translates into 2.20 kpc at our adopted distance of 5.9 Mpc. Integration of the B -band profile gives a total apparent magnitude of $B_T = 11.48$, which is comparable with the value of 11.10 given by Sandage & Tammann (1987) or the RC3 value of 11.32. This corresponds to an absolute magnitude $M_T^{0,i}(B) = -17.45$ and a total blue luminosity of $1.5 \times 10^9 L_{B\odot}$ at the distance of 5.9 Mpc. The optical parameters are summarized in Table 6.

4. H I CONTENT AND DISTRIBUTION

4.1. NGC 24

4.1.1. Global Properties

Once the correction for the primary beam attenuation had been applied, the flux in each individual channel was summed to give the global H I profile of Figure 3 (*left*). An intensity-weighted systemic velocity of 547 ± 3 km s⁻¹ and a midpoint heliocentric radial velocity of $V_\odot = 549 \pm 3$ km s⁻¹ were derived. The measured profile widths at the 20% and 50% levels are $W_{20} = 218$ km s⁻¹

TABLE 4
OPTICAL PARAMETERS OF NGC 24

Parameter	Value
R.A. (J2000.0) ^a	00 ^h 09 ^m 56 ^s .6
Decl. (J2000.0) ^a	-24°57'43"0
Type ^a	SA(s)c III
Distance ^b	6.8 Mpc
Mean axis ratio ^c ($q = b/a$).....	$q = 0.26$
Inclination ($q_0 = 0.15$) ^{c,d}	$i = 78^\circ$
Mean position angle ^d	$\theta = 225^\circ$
Major axis diameter at $\mu_B = 25.0$ mag arcsec ⁻²	$D_{25} = 5'.9$
Minor axis diameter at $\mu_B = 25.0$ mag arcsec ⁻²	$d_{25} = 1'.6$
Holmberg radius ($\mu_B = 26.6$ mag arcsec ⁻²).....	$R_{H0} = 4'.0$
Corrected central surface brightness (exponential disk) ^e	$I(0)_c = 20.67, B(0)_c = 22.12$
Scale length (exponential disk).....	$\alpha^{-1} = 1.42$ kpc
Total apparent B magnitude.....	$B_T = 12.13$
Corrected apparent B magnitude.....	$B_T^{0,i} = 11.75$
Corrected absolute B magnitude.....	$M_B^{0,i} = -17.41$
Total blue luminosity ^f	$L_T(B) = 1.4 \times 10^9 L_{\odot}$

^a RC3.

^b Tully (1988). Here, $1' = 2.0$ kpc.

^c For $1.5 \leq R \leq 3.0$.

^d Calculated by $\cos^2 i = (q^2 - q_0^2)/(1 - q_0^2)$, following Bottinelli et al. (1983).

^e Line-of-sight integration correction is $2.5 \log R_{25} = 1.575$ (RC3).

^f With $M_{B\odot} = +5.43$ (Allen 1976).

TABLE 5
B-BAND LUMINOSITY PROFILE OF NGC 45

Radius (arcsec)	μ_B (mag arcsec ⁻²)
2.3.....	22.17
11.7.....	22.43
16.4.....	22.54
21.1.....	22.66
25.8.....	22.77
30.4.....	22.90
35.1.....	23.08
44.5.....	23.22
58.5.....	23.53
72.6.....	23.79
86.6.....	24.12
100.7.....	24.29
114.7.....	24.49
128.8.....	24.73
142.8.....	24.95
156.8.....	25.06
170.9.....	25.16
184.9.....	25.36
199.0.....	25.64
213.0.....	25.89
227.1.....	25.99
241.1.....	26.38
255.1.....	26.96
269.2.....	27.12
283.2.....	27.70
297.3.....	27.99
311.3.....	28.43
325.4.....	29.02

NOTE.—These values taken from Romanishin et al. (1983).

and $W_{50} = 208 \text{ km s}^{-1}$. This can be compared with the HIPASS (Koribalski et al. 2004) values of $V_{\odot} = 554 \text{ km s}^{-1}$, $W_{20} = 223 \text{ km s}^{-1}$, and $W_{50} = 210 \text{ km s}^{-1}$.

The integrated flux of $54 \pm 5 \text{ Jy km s}^{-1}$ is comparable with the HIPASS measurement of $50.3 \text{ Jy km s}^{-1}$ (Koribalski et al. 2004). It implies a total H I mass of $(5.87 \pm 0.5) \times 10^8 \mathcal{M}_{\odot}$, somewhat higher than the value of $(4.98 \pm 0.4) \times 10^8 \mathcal{M}_{\odot}$ given by Huchtmeier & Seiradakis (1985) for a distance of 6.8 Mpc. It appears that no flux was missed by our synthesis observations.

4.1.2. Spatial Distribution

A moment analysis (with the *momnt* task in AIPS) produced the total H I emission map of Figures 4 (*right, gray scale*) and 5 (*left*, expressed as column density contours and superposed on a DSS image of the galaxy). The distribution, which is really symmetrically distributed, stretches out to $\sim 10'$ in diameter ($\sim 1.3 R_{\text{Ho}}$ at a level of $\sim 10^{20} \text{ atoms cm}^{-2}$). Concentric elliptical averaging corrected by a factor $\cos i$ gave the H I radial profile illustrated in Figure 6 (*left*).

The H I surface density peaks at the center of the galaxy and then decreases as a function of radius. As compared with other morphological types of galaxies (see Fig. 10 in Swaters et al. 2002), this profile is more typical of Sd spiral galaxies (in shape and amplitude) than LSB galaxies. The morphological, optical, and H I properties of NGC 24 point out that this spiral can be considered to be at the transition between normal and LSB galaxies. This distribution is used in § 6 to derive the dynamical contribution of the H I disk.

4.2. NGC 45

4.2.1. Global Properties

The H I properties of NGC 45 were derived in a way similar to that for NGC 24. Figure 3 (*right*) gives the global H I profile once the correction for the primary beam attenuation was applied. The total flux density of $186 \pm 19 \text{ Jy km s}^{-1}$ (compared with $195.8 \text{ Jy km s}^{-1}$ in HIPASS; Koribalski et al. 2004) corresponds to an H I mass of $(1.52 \pm 0.2) \times 10^9 \mathcal{M}_{\odot}$, which is compared with

TABLE 6
OPTICAL PARAMETERS OF NGC 45

Parameter	Value
R.A. (J2000.0) ^a	00 ^h 14 ^m 03 ^s .2
Decl. (J2000.0) ^a	-23°11'01".0
Type ^a	SA(s)dm IV-V
Distance ^b	5.9 Mpc
Mean axis ratio ($q = b/a$) ^c	$q = 0.73$
Inclination ($q_0 = 0.22$) ^{d,e}	$i = 55^\circ \pm 5^\circ$
Position angle ^c	$\theta = 145^\circ \pm 5^\circ$
Major axis diameter at $\mu_B = 25.0 \text{ mag arcsec}^{-2d}$	$D_{25} = 5'.8$
Minor axis diameter at $\mu_B = 25.0 \text{ mag arcsec}^{-2d}$	$d_{25} = 4'.2$
Holmberg radius ($\mu_B = 26.6 \text{ mag arcsec}^{-2d}$).....	$R_{\text{Ho}} = 4'.8$
Corrected central surface brightness (exponential disk) ^d	$B(0)_c = 22.51$
Scale length (exponential disk).....	$\alpha^{-1} = 2.20 \text{ kpc}$
Total apparent B magnitude ^d	$B_T = 11.48$
Corrected apparent B magnitude.....	$B_{T,i}^{0,i} = 11.40$
Corrected absolute B magnitude.....	$M_B^{0,i} = -17.45$
Total blue luminosity ^f	$L_T(B) = 1.4 \times 10^9 L_{\odot}$

^a RC3.

^b Tully 1988. Here, $1' = 1.72 \text{ kpc}$.

^c Romanishin et al. (1983).

^d Puche & Carignan (1988).

^e Calculated by $\cos^2 i = (q^2 - q_0^2)/(1 - q_0^2)$, following Bottinelli et al. (1983).

^f With $M_{B\odot} = +5.43$ (Allen 1976).

FIG. 3.—H I global profile for NGC 24 (*left*) and NGC 45 (*right*) obtained by integrating the H I emission in each channel map. The arrows indicate the systemic velocity as computed from the profiles.

$(1.98 \pm 0.1) \times 10^9 M_{\odot}$ (Huchtmeier & Seiradakis 1985) for a distance of 5.9 Mpc. This seems to indicate that $\sim 20\%$ of the flux is missing, probably due to missing short spacings in the VLA observations. Also derived from the profile is the midpoint systemic velocity of $470 \pm 3 \text{ km s}^{-1}$ and the intensity-weighted systemic velocity of $473 \pm 3 \text{ km s}^{-1}$. The measured profile widths are $W_{20} = 180 \text{ km s}^{-1}$ and $W_{50} = 167 \text{ km s}^{-1}$. This can be compared to the HIPASS values of $V_{\odot} = 467 \text{ km s}^{-1}$, $W_{20} = 185 \text{ km s}^{-1}$, and $W_{50} = 167 \text{ km s}^{-1}$ (Koribalski et al. 2004).

4.2.2. Spatial Distribution

Figures 7 (*right*) and 8 (*left*, in contours superposed on a DSS photograph of the galaxy) show the distribution of H I surface densities obtained by the moment analysis. The H I disk is regular and extends to $\sim 20''$ in diameter ($\sim 2.1 R_{\text{H}0}$ at a level of $\sim 10^{20} \text{ atoms cm}^{-2}$).

The shape and amplitude of the radial distribution of the H I surface density (Fig. 6, *right*) is typical of what is seen in LSB spiral galaxies, showing a depression in the central regions with a low gas surface density level (see Fig. 10 in Swaters et al. [2002] for comparison). Morphological, photometric, and gaseous prop-

erties of NGC 45 make this spiral a genuine LSB galaxy. This profile is used in § 6 to evaluate the dynamical importance of the NGC 45 H I component.

5. VELOCITY FIELD AND ROTATION CURVE

5.1. NGC 24

Figure 5 (*right*) shows the velocity field obtained by the moment analysis, where the radial velocities were calculated by taking the intensity-weighted mean of each line profile for pixels above the 1.8σ level in the $40'' \times 40''$ resolution data cube. This velocity field is regular, with no sign of large-scale deviation from axial symmetry. From the shape of the isovelocity contours, one can already infer that this galaxy does not have a solid-body rotation curve (the contours are not parallel) but rather tends to be flat in the outer parts.

In order to extract the rotation curve, the *rotcur* task (Begeman 1989) of the GIPSY program (van der Hulst et al. 1992) was used. The task makes a least-squares fitting of a tilted-ring model to the velocity field. A solution has to be found for the following kinematical parameters in order to obtain the circular velocity as a

FIG. 4.—NGC 24: contours of the DSS optical image (*left*) and the gray-scale total H I map displayed using a logarithmic stretch (*right*).

FIG. 5.—Total H I map (*left*) and H I velocity field (*right*) superposed on a DSS image of the galaxy NGC 24. The contours are at surface density levels of 0.06, 0.31, 1.25, 2.19, 3.13, 4.07, 5.01, and 5.95×10^{21} atoms cm^{-2} . Velocity contours are drawn from 460 to 640 km s^{-1} in steps of 15 km s^{-1} . The beam size of $40'' \times 40''$ is shown in the bottom left corner of the images.

function of radius: the coordinates of the rotation center, the systemic velocity (v_{sys}), the inclination (i), and the position angle (P.A.) of the major axis. To diminish the importance of deprojection errors at such an inclination, radial velocities in an opening angle of 80° about the minor axis were rejected for the least-squares fitting, and a cosine weighting function giving more importance to points near the major axis was used.

The fitting procedure is described in Chemin et al. (2006). Briefly, the rotation center and systemic velocity are searched for first, followed by the inclination and the position angle. The derived systemic velocity is $554 \pm 1 \text{ km s}^{-1}$, which is comparable to the value obtained with the global H I profile. The kinematical inclination is $64^\circ \pm 3^\circ$. This is significantly lower than the optical inclination of 78° and the value found by an ellipse fitting to the H I isophotes (76°). The low spatial resolution of the data combined with the high inclination of the disk probably explains such a difference. The choice of either the photometric or the kinematical value does not influence the main result of this work (see §§ 6 and 7). Hence, the kinematical inclination is chosen for NGC 24

throughout this article and all derived quantities (rotation curve, mass-to-light ratio, etc.) are given adopting this value, except where explicitly mentioned. The kinematical position angle is $229^\circ \pm 1^\circ$. This value remains comparable to the one derived from the photometry ($225^\circ \pm 5^\circ$).

A rotation curve is finally obtained (Fig. 9 and Table 7) by fixing all the other parameters at constant values because no warp is found in NGC 24. At each radius, the quoted error bar of the velocity point given in Table 7 corresponds to the maximum value between the formal error calculated by *rotcur* (1σ dispersion of the fitted velocity parameter) and the largest velocity difference between the solution for both sides and the separate solutions for the approaching and receding halves (Carignan & Puche 1990a).

5.2. NGC 45

The velocity field of NGC 45, obtained from the analysis of the $42'' \times 42''$ resolution data cube by discarding pixels under a 1.6σ level, is shown in Figure 8 (*right*). The same procedure used to derive the rotation curve of NGC 24 is used for NGC 45.

FIG. 6.—Radial distribution of H I surface density for NGC 24 (*left*) and NGC 45 (*right*), obtained by averaging the total H I map in circular annuli in the plane of the galaxy.

FIG. 7.—NGC 45: contours of the DSS optical image (*left*) and gray-scale total H I map displayed using a logarithmic stretch (*right*).

To lessen the errors due to the deprojection, all points in a sector of 60° around the minor axis were discarded from the fitting. A systemic velocity of $467 \pm 2 \text{ km s}^{-1}$ is found, which agrees to within the errors with the value obtained using the global profile and agrees with the one given by Adler & Liszt (1989). The inclination is found to be constant as a function of radius ($51^\circ \pm 2^\circ$) and is in relative agreement with the photometric value within the error ($55^\circ \pm 5^\circ$).

A study of the H I isophotes shows that the outermost contour is slightly twisted with respect to the inner isophotes. The outer isovelocity contours are also twisted as a function of radius. A kinematical twist of the H I plane is indeed detected with the tilted-ring model (Fig. 9). The P.A. decreases by $\sim 25^\circ$ from the inner to the outer regions, whereas i remains constant. A kinematical warp or a simple twist of the kinematical major axis is very common in the Sculptor group H I disks (e.g., Carignan & Puche 1990a) and more generally in spiral galaxies (García-Ruiz et al. 2002).

The final rotation curve is thus derived by fixing the center coordinates, systemic velocity, and inclination at constant values and by leaving the P.A. free as a function of radius. The rotation curve is given in Table 8 and displayed in Figure 9. Here, again, no significant asymmetry is detected between the rotation curves of the approaching and receding sides of the disk. Table 8 also gives the radial variation of the P.A., with its errors computed as the maximum value between the formal error calculated by *rotcur* (1σ dispersion of the fitted angle) and the largest angle difference between the fitted value for both sides and the separate fitted values for the approaching and receding halves.

6. STUDY OF THE MASS DISTRIBUTION

A preliminary study of the mass distribution is presented here using the present low-resolution H I data. This should give a first good estimate of the dark-to-luminous mass ratio in those two galaxies and allow us to get a good idea whether the dark matter

FIG. 8.—Total H I map (*left*) and H I velocity field (*right*) superposed on a DSS image of the galaxy NGC 45. The contours are at surface density levels of 0.13, 0.62, 1.11, 1.60, 2.09, 2.58, and $3.07 \times 10^{21} \text{ atoms cm}^{-2}$. Velocity contours are drawn from 385 to 550 km s^{-1} in steps of 15 km s^{-1} . The beam size of $42'' \times 42''$ is shown in the bottom left corner of the images.

FIG. 9.—Rotation curves of NGC 24 (*left*) and NGC 45 (*middle*) and radial profile of the inclination and the major axis position angle of NGC 45 (*right*), as derived from the tilted-ring models. Filled symbols correspond to the values for both sides fitted simultaneously, and open upward and downward triangles correspond to the values for the receding and approaching sides, respectively, fitted separately. The inclination is shown as asterisks and the adopted inclination as a dashed line.

component dominates at all radii, as seen in dwarf irregular galaxies (e.g., Carignan & Beaulieu 1989), in some late-type spiral galaxies (e.g., Côté et al. 1991), or in other LSB galaxies (e.g., de Blok & McGaugh 1997). As for the other papers from this series, only the best-fit mass models are presented for the two galaxies. These models are very close to the maximum disk case. Notice that for NGC 45 another model that uses the mass-to-light ratio expected from stellar population synthesis (SPS) models is presented (see § 7).

6.1. Two-Component Model

One can refer to Carignan (1985), Carignan & Freeman (1985), and the other papers in this series for a detailed discussion of the two-component (dark and luminous) model. Because NGC 24 has a very small bulge and NGC 45 has no bulge, as seen in Figure 1, no attempt to include a bulge component in the models was made. For NGC 24, the I profile derived in § 3 was used to derive the contribution of the stellar component. It was transformed into the B band according to Carignan (1983). For NGC 45, the B -band luminosity profile of Romanishin et al. (1983) was used. The contribution of the gaseous component was derived assuming that all the gas is confined in an infinitely thin disk and using the H I radial surface densities (Fig. 6), which were multiplied by four-thirds to take into account primordial helium.

The dark halo is modeled by an isothermal sphere that is described by two basic parameters: the core radius r_c and the one-dimensional velocity dispersion σ . A third quantity, the central density of the halo, is related to the two others by $\rho_0 = 9\sigma^2/4\pi Gr_c^2$. Essentially, the mass model depends on three parameters: the amplitude scaling of the luminous disk $(\mathcal{M}/L_B)_*$ (the mass-to-light ratio of the stellar disk), the radial scaling r_c , and the velocity scaling σ of the halo. To determine the combination of the three parameters that best reproduces the observed rotation curve, a best-fitting method was used, without any constraints on the parameter values. By exploring a grid of values in the three-

parameter space, a set $[(\mathcal{M}/L_B)_*, r_c, \sigma]$ is found leading to the smallest χ^2 for the fit. Once an approximate minimum has been identified, the solution is refined by improving the step resolution for the three parameters. This routine is reiterated until a final set of parameters is obtained. The mass-to-light ratio of the stellar disk is supposed to be constant as a function of radius and the errors on the derived model parameters are established from the 90% confidence level for both galaxies.

Notice that no attempt to explore different functional forms for the halo was made with these H I data. A comparison between a cuspy halo, like e.g., the NFW one (Navarro et al. 1997), and a core-dominated halo, like the one presented here, indeed requires high spatial resolution data to accurately map the inner rising part of a rotation curve (Swaters et al. 2000). Such mass models will be presented elsewhere when three-dimensional optical Fabry-Pérot data become available (L. Chemin et al. 2006, in preparation).

6.2. Mass-Modeling Results

The results from the best-fit mass model for NGC 24 are illustrated in Figure 10 (*left*) and given in Table 9. The model gives a $(\mathcal{M}/L_B)_*$ of 2.5 ± 0.3 for a total disk mass of $\sim 3.4 \times 10^9$. The H I + He gas, with a total mass of $\sim 7.4 \times 10^8 \mathcal{M}_\odot$, provides only $\sim 20\%$ of the luminous mass and is therefore not very important dynamically. The parameters for the dark halo are $r_c = 5.6 \pm 1.5$ kpc and $\sigma = 65.0 \pm 4.0$ km s $^{-1}$. This gives a central density for the dark halo of $0.022 \mathcal{M}_\odot$ pc $^{-3}$. Notice here that the use of a rotation curve derived by a tilted-ring model with an inclination fixed to the photometric value of 78° would slightly reduce the $(\mathcal{M}/L_B)_*$ to 2.0 without changing the other parameters.

TABLE 8
H I ROTATION CURVE AND POSITION ANGLE OF THE KINEMATICAL
MAJOR AXIS FOR NGC 45

Radius (arcsec)	V_{rot} (km s $^{-1}$)	P.A. (deg)
42.....	53.2 ± 3.6	144.0 ± 11.0
84.....	70.1 ± 1.3	148.6 ± 5.9
126.....	79.1 ± 1.7	148.2 ± 1.0
168.....	87.4 ± 0.3	147.0 ± 0.3
210.....	93.4 ± 0.4	147.2 ± 0.7
252.....	97.7 ± 2.2	145.9 ± 1.3
294.....	102.3 ± 1.6	143.0 ± 1.0
336.....	105.9 ± 0.3	139.3 ± 0.2
378.....	103.4 ± 1.4	136.5 ± 0.1
420.....	101.0 ± 0.9	132.7 ± 1.6
462.....	100.9 ± 1.0	129.0 ± 1.5
504.....	99.9 ± 1.5	126.4 ± 1.3
546.....	99.8 ± 0.3	124.6 ± 0.7
588.....	100.0 ± 0.6	124.9 ± 0.4

TABLE 7
H I ROTATION CURVE FOR NGC 24

Radius (arcsec)	V_{rot} (km s $^{-1}$)	Error (km s $^{-1}$)
40.....	56.6	6.4
80.....	82.5	2.7
120.....	91.8	0.8
160.....	99.2	0.8
200.....	103.6	2.2
240.....	106.2	1.8
280.....	109.4	3.5
320.....	109.7	2.0

FIG. 10.—Mass models using the best-fit method for NGC 24 (*left*) and NGC 45 (*middle*). The model on the right is for NGC 45 with $(\mathcal{M}/L_B)_* = 2.0$. The solid line is for the best-fit model to the data (*diamonds*). The contribution of the different components (stellar disk, H I component corrected for the He content, and dark halo) are identified.

The results from the best-fit mass model for NGC 45 are illustrated in Figure 10 (*middle*) and given in Table 10. The parameters are $(\mathcal{M}/L_B)_* = 5.2 \pm 1.0$, $r_c = 6.2 \pm 0.6$ kpc, and $\sigma = 55.0 \pm 1.0$ km s $^{-1}$, which correspond to a central density for the halo of $\rho = 0.013 \mathcal{M}_\odot \text{pc}^{-3}$. Total masses of $5.3 \times 10^9 \mathcal{M}_\odot$ and $2.1 \times 10^9 \mathcal{M}_\odot$ are found for the stellar and gaseous disks, respectively.

7. DISCUSSION

The extent of the H I disk is $R_{\text{HI}} = 1.3R_{\text{H0}} = 7.3\alpha^{-1}$ for NGC 24 and $R_{\text{HI}} = 2.1R_{\text{H0}} = 7.9\alpha^{-1}$ for NGC 45. The H I extent of NGC 24 is very similar to the H I extent of the Sculptor late-type spiral galaxies NGC 247, NGC 300, and NGC 7793 (1.2, 1.5, and 1.4 R_{H0} , respectively). Again, this suggests that NGC 24 is very similar to normal late-type spiral galaxies, as also claimed in § 4.1.2.

The best-fit mass model of NGC 24 gives a $(\mathcal{M}/L_B)_*$ for the stellar disk of 2.5 ± 0.3 . From the observed colors of $0.56 \lesssim (B - V) \lesssim 0.60$ for NGC 24 (RC3), SPS models predict a mass-to-light ratio for the stellar disk of $1 \lesssim (\mathcal{M}/L_B)_* \lesssim 1.2$ (Bell & de Jong 2001). The mass-to-light ratio is thus twice the one expected from SPS models. This result remains unchanged when using $(\mathcal{M}/L_B)_* = 2.0$, as found when using the photometric inclination instead of the kinematical value.

The case of NGC 45 is even more problematic since the derived $(\mathcal{M}/L_B)_*$ from the best-fit model is nearly 3 times greater than the value expected from SPS models: 5.2 versus $1.7 \lesssim (\mathcal{M}/L_B)_* \lesssim 2.2$ (Bell & de Jong 2001), based on the observed $(B - V)$ color of 0.71 ± 0.03 (RC3).

Similar high $(\mathcal{M}/L_B)_*$ values are often found in LSB galaxies when fitting maximum disk models (de Blok & McGaugh 1997; de Blok et al. 2001; de Blok & Bosma 2002; Swaters et al. 2003). An interpretation of these results is that the maximum disk hypothesis must not hold for LSB galaxies (de Blok et al. 2001). As a consequence, these galaxies appear to be dominated by dark matter at all radii when mass models preferentially use a mass-to-light ratio consistent with SPS models (de Blok & McGaugh 1997; de Blok et al. 2001; de Blok & Bosma 2002).

Such a model is illustrated for NGC 45 in Figure 10 (*right*), using a $(\mathcal{M}/L_B)_*$ value of 2.0 (see also Table 11). This value is chosen to be representative of the expected $(\mathcal{M}/L_B)_*$ range given by the SPS models (see above). Indeed, it can be seen that the dark component is dominant over almost the whole stellar disk, although with the noticeable exception of the very innermost regions.

This new model nevertheless highly underestimates the first two points of the rotation curve, thus giving a worse fit ($\chi^2 \sim 8$) than the best-fit model ($\chi^2 \sim 3$). The quality of the fit also

TABLE 9
BEST-FIT TWO-COMPONENT MODEL FOR NGC 24

Parameter	Value
Luminous Disk Component	
$(\mathcal{M}/L_B)_*$	$2.5 \mathcal{M}_\odot/L_\odot$
$\mathcal{M}_{\text{disk}}$	$3.4 \times 10^9 \mathcal{M}_\odot$
$\mathcal{M}_{\text{HI+He}}$	$7.4 \times 10^8 \mathcal{M}_\odot$
Dark Halo Component	
r_c	5.6 kpc
σ	65 km s $^{-1}$
ρ_0	$0.022 \mathcal{M}_\odot \text{pc}^{-3}$
At R_{H0} ($r = 7.9$ kpc)	
ρ_{halo}	$0.004 \mathcal{M}_\odot \text{pc}^{-3}$
$\mathcal{M}_{\text{dark}}/\mathcal{M}_{\text{lum}}$	4.0
$(\mathcal{M}/L_B)_{\text{dyn}}$	$15.3 \mathcal{M}_\odot/L_\odot$
$\mathcal{M}_{\text{dark+lum}}$	$2.0 \times 10^{10} \mathcal{M}_\odot$
At Last Measured Point ($R = 10.5$ kpc)	
ρ_{halo}	$0.0022 \mathcal{M}_\odot \text{pc}^{-3}$
$\mathcal{M}_{\text{dark}}/\mathcal{M}_{\text{lum}}$	6.0
$(\mathcal{M}/L_B)_{\text{dyn}}$	$21.2 \mathcal{M}_\odot/L_\odot$
$\mathcal{M}_{\text{dark+lum}}$	$2.8 \times 10^{10} \mathcal{M}_\odot$

TABLE 10
BEST-FIT TWO-COMPONENT MODEL FOR NGC 45

Parameter	Value
Luminous Disk Component	
$(\mathcal{M}/L_B)_*$	$5.2 \mathcal{M}_\odot/L_\odot$
$\mathcal{M}_{\text{disk}}$	$5.3 \times 10^9 \mathcal{M}_\odot$
$\mathcal{M}_{\text{HI+He}}$	$2.1 \times 10^9 \mathcal{M}_\odot$
Dark Halo Component	
r_c	6.2 kpc
σ	55 km s $^{-1}$
ρ_0	$0.013 \mathcal{M}_\odot \text{pc}^{-3}$
At R_{H0} ($r = 8.3$ kpc)	
ρ_{halo}	$0.003 \mathcal{M}_\odot \text{pc}^{-3}$
$\mathcal{M}_{\text{dark}}/\mathcal{M}_{\text{lum}}$	1.8
$(\mathcal{M}/L_B)_{\text{dyn}}$	$18.0 \mathcal{M}_\odot/L_\odot$
$\mathcal{M}_{\text{dark+lum}}$	$1.8 \times 10^{10} \mathcal{M}_\odot$
At Last Measured Point ($R = 16.7$ kpc)	
ρ_{halo}	$0.0005 \mathcal{M}_\odot \text{pc}^{-3}$
$\mathcal{M}_{\text{dark}}/\mathcal{M}_{\text{lum}}$	4.0
$(\mathcal{M}/L_B)_{\text{dyn}}$	$36.2 \mathcal{M}_\odot/L_\odot$
$\mathcal{M}_{\text{dark+lum}}$	$3.7 \times 10^{10} \mathcal{M}_\odot$

TABLE 11
TWO-COMPONENT MODEL FOR NGC 45 WITH $(\mathcal{M}/L) = 2.0$

Parameter	Value
Luminous Disk Component	
$(\mathcal{M}/L_B)_*$	$2.0 \mathcal{M}_\odot/L_\odot$
$\mathcal{M}_{\text{disk}}$	$2.0 \times 10^9 \mathcal{M}_\odot$
$\mathcal{M}_{\text{H I+He}}$	$2.1 \times 10^9 \mathcal{M}_\odot$
Dark Halo Component	
r_c	4.2 kpc
σ	58 km s ⁻¹
ρ_0	$0.032 \mathcal{M}_\odot \text{ pc}^{-3}$
At $R_{\text{H0}} (r = 8.3 \text{ kpc})$	
ρ_{halo}	$0.003 \mathcal{M}_\odot \text{ pc}^{-3}$
$\mathcal{M}_{\text{dark}}/\mathcal{M}_{\text{lum}}$	4.7
$(\mathcal{M}/L_B)_{\text{dyn}}$	$18.8 \mathcal{M}_\odot/L_\odot$
$\mathcal{M}_{\text{dark+lum}}$	$1.9 \times 10^{10} \mathcal{M}_\odot$
At Last Measured Point ($R = 16.7 \text{ kpc}$)	
ρ_{halo}	$0.0005 \mathcal{M}_\odot \text{ pc}^{-3}$
$\mathcal{M}_{\text{dark}}/\mathcal{M}_{\text{lum}}$	7.8
$(\mathcal{M}/L_B)_{\text{dyn}}$	$35.8 \mathcal{M}_\odot/L_\odot$
$\mathcal{M}_{\text{dark+lum}}$	$3.7 \times 10^{10} \mathcal{M}_\odot$

decreases as one goes toward the minimum disk hypothesis [for $(\mathcal{M}/L_B)_* = 0$, $\chi^2 \sim 11$]. Such a result is in agreement with what is found for other LSB galaxies, as illustrated in de Blok & Bosma (2002). For several galaxies from their sample, the minimum disk hypothesis or a model using a low $(\mathcal{M}/L_B)_*$ does not always provide a better fit than the maximum disk hypothesis.

One finally notices that higher $(\mathcal{M}/L_B)_*$ values should be expected if a correction for beam-smearing was applied or if a higher angular resolution was used for the innermost velocity points of the curves. Indeed, it should give more steeply rising rotation curves in their inner parts than those presented here (see, e.g., Swaters et al. 2000). This would worsen the discrepancy found between the low $(\mathcal{M}/L_B)_*$ values from SPS models and the maximum disk hypothesis. Therefore, if one finally admits that the maximum disk hypothesis is ruled out for LSB galaxies (as favored in de Blok et al. 2001), a more cuspy halo than the pseudo-isothermal sphere should perhaps be used to better fit the inner velocity points of NGC 45 with a low $(\mathcal{M}/L_B)_*$. This claim will be tested in a forthcoming article.

8. SUMMARY AND CONCLUSIONS

An optical and H I study of NGC 24 and NGC 45 has been presented. The main results are as follows:

1. From the surface photometry of NGC 24 and NGC 45, it is found that while NGC 24 is on the faint side for normal galaxies, NGC 45 can be considered to be a bona fide LSB galaxy. However, both galaxies have very similar absolute magnitudes, approximately -17.4 .

2. The H I distribution for NGC 24 and NGC 45 extends to ~ 1.3 and $2.1 R_{\text{H0}}$, respectively, at a level of $\sim 10^{20}$ atoms cm⁻². The H I extent of NGC 24 is very similar to the H I extent of the Sculptor late-type spiral galaxies NGC 247, NGC 300, and NGC 7793 (1.2, 1.5, and $1.4 R_{\text{H0}}$, respectively).

3. The overall velocity fields of the two galaxies are very regular. NGC 45 exhibits a twist of the kinematical major axis, showing an $\sim 25^\circ$ variation of its major axis position angle as a function of radius. However, its disk does not have a classical warp, since the inclination remains constant.

4. The rotation curves derived from the velocity fields rise slowly and flatten at a velocity of ~ 110 and ~ 100 km s⁻¹, respectively. It extends out to ~ 11 kpc for NGC 24 and to ~ 17 kpc for NGC 45, which corresponds to ~ 7.5 scale lengths in both cases.

The rotation curves, combined with the luminosity profiles, were used to study the mass distribution of NGC 24 and NGC 45. Using a best-fit model, the main results are:

1. The $(\mathcal{M}/L_B)_* = 2.5$, $r_c = 5.6$ kpc, and $\sigma = 65$ km s⁻¹ for NGC 24, and $(\mathcal{M}/L_B)_* = 5.2$, $r_c = 6.2$ kpc, and $\sigma = 55$ km s⁻¹ for NGC 45.

2. In both galaxies, the dark halo is the main contributor to the total mass of the galaxies, with a contribution of more than $\sim 80\%$ at the last measured point. Since the best-fit models are close to the maximum disk case, this can be considered a lower limit.

3. The $(\mathcal{M}/L_B)_*$ of 5.2 found for NGC 45 and 2.5 for NGC 24 are high when compared with the values predicted by stellar population synthesis models for galactic disks of same colors as NGC 24 and NGC 45. This result is similar to what is seen in other LSB galaxies. When a model for NGC 45 uses a $(\mathcal{M}/L_B)_*$ of 2.0, a value that is adopted from SPS models, it allows the galaxy mass to be entirely dominated by the dark component, but it also severely underestimates the velocity of the innermost points of the rotation curve.

This article is the first in a series that aims at measuring the shape of the mass density profile for the dark component of NGC 24 and NGC 45. When higher resolution optical kinematical H α data obtained with Fabry-Pérot interferometry become available, more accurate mass models of those galaxies will be presented.

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