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STAR FORMATION THRESHOLDS IN LOW SURFACE BRIGHTNESS GALAXIES

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ABSTRACT

Low Surface Brightness (LSB) galaxies appear to have low star formation rates despite their often quite normal H I contents as judged from global H I properties such as $M_{\rm H\,I}/L$ and $M_{\rm H\,I}/M_T$ ratios. H I imaging with the Very Large Array of the National Radio Astronomy Observatory (the NRAO is operated by Associated Universities Inc. under contract with the National Science Foundation) of eight LSB galaxies shows that the H I is extended compared with the optical size and has average surface densities which are about a factor 2 lower than in High Surface Brightness (HSB) galaxies of the same type. The resolution of the H I imaging allows a rough rotation curve analysis for evaluating the critical density for star formation as formulated by Kennicutt [ApJ, 344, 685 (1989)]. The observed H I surface densities systematically fall below this critical density for most of the galaxies in this sample, in agreement with the low current star formation rates. From the optical surface photometry we conclude that the galaxies studied are in general late-type galaxies dominated by an exponential disk with a typical scale length of a few kpc. The $B-R$ and $V-I$ colors of the LSB galaxies are a few tenths of a magnitude bluer than those of HSB galaxies indicating that the disks of these galaxies have a mean young age.

1. INTRODUCTION

Low Surface Brightness (LSB) galaxies are galaxies which have a central disk surface brightness which is systematically fainter than the canonical $\mu_B(0)=21.65$ mag arcsec^{-2} (Freeman 1970; see also van der Kruit 1987). In general, LSB disk galaxies are defined as those having $\mu_B(0)$ fainter than 23.0 mag arcsec^{-2} and/or a mean surface brightness within three scale lengths 1.5 mag arcsec^{-2} fainter than a Freeman disk (see Bothun *et al.* 1993). Until now LSB galaxies were a relatively poorly studied group of objects. Recently, however, several papers have appeared in the literature dealing with the properties of LSB galaxies in a systematic way (e.g., Bothun *et al.* 1987; Schombert & Bothun 1988; Impey *et al.* 1988; Schombert *et al.* 1992; Bothun *et al.* 1990; Bothun *et al.* 1993).

In a study of the neutral hydrogen content of red spiral galaxies, van der Hulst *et al.* (1987) discovered that these galaxies, despite having different global $M_{\rm H\,I}/L$ ratios and H I extents, all exhibited very low H I surface densities. Two of the three galaxies studied also had rather low optical central surface brightness, which suggests a relation between low optical surface brightness and low H I surface densities.

Since the original proposal of Schmidt (1959) of a star formation law based on gas density, there have been subsequent suggestions of a gas density threshold for the formation of massive stars (Quirk 1972; Einasto 1972). Kennicutt (1989) has been quite successful in following up

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TABLE 1. VLA observing parameters.

	UGC 0128	UGC 0628	UGC 1230	UGC 5005	UGC 5209	UGC 5750	UGC 5999	UGC 6614
Field Center								
R.A. (1950)	$00^h11^m12^s$	$00^h58^m18^s$	$01^h42^m42^s$	$09^h21^m36^s$	$09^h42^m00^s$	$10^h33^m00^s$	$10^h50^m36^s$	$11^h36^m36^s$
Declination (1950)	35°43′00″	19°13′00″	25°16′00″	22°29′00″	32°29′00″	21°16′00″	07°54′00″	17°25′00″
Observation Date	1987 Jan. 10	1987 Jan. 00	1987 Jan. 10,16	1987 Jan. 12	1987 Jan. 14	1987 Jan. 14	1987 Jan. 12	1987 Jan 12,14
No. of Antennae	25	25	25	25	25	25	25	25
VLA Configuration	C	C	C	C	C	C	C	C
On source integration time (hours)	1.83	1.77	1.73	1.57	1.44	1.73	1.06	1.54
FWHM Synthesized beam	24.8 × 23.4	25.0 × 23.0	23.9 × 23.4	24.4 × 23.1	24.4 × 23.5	24.4 × 21.8	24.2 × 20.8	24.8 × 22.4
Central Velocity (km s^{-1})	4573	4890	3839	3845	560	4168	3400	6351
Total Bandwidth (Mhz)	3.03	3.03	3.03	3.03	3.03	3.03	3.03	3.03
Number if Frequency Channels	31	31	31	31	31	31	31	31
Velocity Resolution/ Channel Spacing (km s^{-1})	21.2	21.3	21.1	21.1	20.7	21.2	21.1	21.5
R.M.S. noise in 40″ × 40″ beam (mJy/Beam)	2.3	2.8	4.0	2.6	2.8	2.7	3.5	3.2

on this idea, demonstrating the utility of a dynamical estimate of the critical density required to stabilize the gas disk. This dynamical criteria for the onset of star formation may be related to disk kinematics, spiral density waves, and the formation of giant molecular clouds or to a dynamical feedback between the disk kinematics and the dark halo potential (e.g. Bosma *et al.* 1988; Athanassoula & Bosma 1989; Franx & de Zeeuw 1992). Kennicutt (1989) analyzed the radial gas distributions in galaxies and found that almost invariably star formation occurs only there where the gas density exceeds some critical value. Galaxies whose gas density is everywhere below this critical density may exist in a relatively quiescent stage over a Hubble time (see Bothun *et al.* 1990). This may explain the characteristics of the galaxies studied by van der Hulst *et al.* (1987) as well as low surface brightness (LSB) disks in general.

An unanswered question is whether LSB spirals are fundamentally different from the normal surface brightness spirals that have received most of the observational attention in the last decades. It is these latter galaxies which define the Hubble sequence, which can be best characterized as a sequence of increasing relative star formation rate (SFR) at the present epoch (e.g., Kennicutt 1983). Despite being late morphological types, the SFR in LSB disks is often quite low (see McGaugh 1992), and it is unclear how these galaxies fit into the Hubble sequence. For instance, the color distribution of LSB disks are normal to rather blue (Schombert *et al.* 1990; McGaugh 1992) which strongly excludes the possibility that these disks are the fossilized remnants which have faded after an initial epoch of star formation a few Gyr ago. LSB spirals may therefore have an evolutionary history quite different from those spirals that define the Hubble sequence. One possible scenario is that after an initial phase of global star formation, LSB spirals ceased to have sufficient gas density to support further large scale star formation. The indication that LSB spirals have quite low metallicities for their disk mass (Webster *et al.* 1983; van der Hulst *et al.* 1987; McGaugh 1992; McGaugh & Bothun 1993a; van der Hulst *et al.* 1993a; Rönnback 1993) certainly supports this idea.

In this paper, we test the idea that LSB spirals have H I surface densities which systematically fall below the star formation threshold. Our sample consists of eight face-on LSB galaxies that all exhibit incipient spiral structure. We emphasize that this sample is not dominated by low mass (e.g., dwarf) LSB galaxies (whose evolutionary history is likely quite different) but rather consists of galaxies with masses typical of an L* galaxy. Surface density distributions in H I have been measured from observations at the Very Large Array (VLA) of the National Radio Astronomy Observatory (NRAO). Six of these galaxies have similar distances (i.e., redshifts) allowing a comparison at comparable linear resolutions.

Throughout this paper we will use heliocentric radial velocities and a Hubble constant of 75 km s^{-1} Mpc^{-1}.

2. OBSERVATIONS AND DATA REDUCTION

Neutral hydrogen observations of UGC 0128, UGC 0628, UGC 1230, UGC 5005, UGC 5209, UGC 5750, UGC 5999, and UGC 6614 were made with the VLA in its 3 km (C) configuration. We used the on-line Hanning smoothing option to improve the signal to noise of the spectra. The observational parameters are summarized in Table 1.

The observations were calibrated using the standard VLA calibration procedures so that the flux densities are on the Baars *et al.* (1977) scale. The calibrated data were further reduced and analyzed using the (NRAO) image processing system AIPS.

For each galaxy a set of 31 channel maps was made. Because of the low surface brightness of the H I in these galaxies we could not use the full resolution of the C array and lowered the resolution to 24″ using a Gaussian taper on the (u,v) data in order to increase the signal to noise. Continuum free line maps were produced by averaging together channel maps which showed no line emission, and then subtracting this average from each individual channel map. In order to improve the signal to noise ratio for low surface brightness emission even more the resulting continuum free maps were then smoothed further with a twodimensional Gaussian to produce two additional sets of maps with circular beam sizes of 40" and 50". The low resolution (50") maps were then used to apply a conditional transfer to the intermediate resolution (40") maps. In this procedure all regions in the 40" maps which corresponded to regions of undetected signal ($<2\sigma$) in the 50" map were "blanked." Spurious signals which passed through the transfer were recognized and blanked. H I column density and velocity field maps were then produced by calculating the zeroth and first moment of the conditionally transferred H I spectra. Contour plots of the H I column density distributions and velocity fields are shown in Fig. 1.

The optical observations consist of CCD imaging in *B*, *V*, and *R* obtained at the Mt. Palomar 60 in., KPNO 0.9 m, La Palma 2.5 m Isaac Newton, and the MDM (McGraw Hill) 1.3 m telescopes. We have *UBVRI* images for UGC 128, UGC 628, UGC 5750, and UGC 1230, and *R*-band images for UGC 5005, UGC 5209, and UGC 5999. The CCD data were calibrated using standard star observations. The surface photometry from the different telescopes agrees to within 0.02 mag for objects in common.

Radial surface brightness profiles were determined from the images using an ellipse fitting program. This program also provides the ellipticity and position angle as a function of radius. The ellipticity data were used to calculate the optical inclinations given in Table 2. Typical errors in surface brightness range from 0.03 mag arcsec^{-2} at the 20 mag arcsec^{-2} surface brightness level to 0.15 mag arcsec^{-2} at the 25 mag arcsec^{-2} surface brightness level. The radial surface brightness distributions are shown in Fig. 2.

3. RESULTS

3.1 Radial H I Surface Density Distributions

Since the primary concern of this study is to determine the characteristics of the H I distribution, the first step was to compute the H I surface density of the galaxies. H I surface density maps are made by scaling the H I column density maps by the cosine of the inclination angle to deproject the image. Since most of the galaxies in the sample are relatively face-on, the inclination corrections are small, and the derived H I surface density measurements are relatively accurate. The inclination for each galaxy was determined by two methods. The first method was to use the axial ratios from the CCD data, and the Holmberg (1958) relation $\cos^2(i)=[(b/a)^2-q_0^2]/[1-q_0^2]$, (where q_0, the intrinsic flattening, is taken to equal 0.2) to calculate the inclination.

The second method involved measuring the major and minor axes of the H I distribution at a column density of 1.4×10^{20} H I atoms cm^{-2} (1.12 $\mathscr{M}_\odot$ pc^{-2}), and then after correcting for beam smearing, using the Holmberg relation.

The inclinations derived from the H I distribution gave systematically greater values than those derived optically. This may reflect a physical characteristic such as a warped H I disk. However, since the H I measurements are affected by beam smearing and have relatively low resolution, the optically derived inclination will be used for the construction of the H I surface density maps.

A third possible method for determining a galaxy's orientation parameters, is to use the velocity field (Warner *et al.* 1973; Bosma 1981). For three of the galaxies, UGC 0128, UGC 1230, and UGC 6614, the velocity field is well enough defined, and the resolution sufficient to try this method. The inclinations are discussed below. The position angles of the kinematical line of nodes agreed to within the errors with the position angles derived from the CCD photometry. The adopted orientation parameters are listed in Table 2.

It should be noted that the derived surface density measurements are an average over the 40" beam, so these values reflect lower limits. At the average distance (50 Mpc) of the six galaxies with similar redshifts (UGC 0128, UGC 0628, UGC 1230, UGC 5005, UGC 5750, and UGC 5999) any H I structure smaller than 10 kpc will be smeared out. For UGC 6614 at a distance of 85 Mpc, any structure smaller than 17 kpc will be smeared out. The peak surface densities listed in Table 2 also represent a lower limit since the local H I may be heavily clumped and have higher values on a smaller scale.

For the case of UGC 6614 the radial H I surface density distribution was derived from the original high resolution (24") map, making a comparison at similar linear resolutions possible. Despite its much smaller distance, no radial distribution was calculated for UGC 5209, since it is essentially unresolved. The radial profiles are shown in Fig. 2.

From the radial surface density distributions we then measured the size of the H I distribution, following Wevers (1984) and Warmels (1986), as the H I extent at a surface density of 1 $\mathscr{M}_\odot$ pc^{-2}. The values are listed in Table 2.

A description of the H I properties and orientation parameters of each individual galaxy follows below:

UGC 0128: The H I distribution is elongated, and suggests an inclination of 60°, consistent with the optically defined value of 57°. The inclination derived from the velocity fields gives a value of 24°. This value is quite uncertain and we adopt the optical inclination for our further analysis.

UGC 0628: No H I was detected in this galaxy, therefore only an upper limit to the H I column density can be derived. If we assume a detection of at least a 3σ signal in a 21 km s^{-1} channel with a root mean square (rms) noise of 3.6 mJy in the low resolution (50") map, then the upper limit to the peak surface density in UGC 0628, is 1.1×10^{20} atoms cm^{-2}.

UGC 1230: Like UGC 0128, the H I distribution suggests a greater value for the inclination than found optically (50° as opposed to 22°). The inclination cannot be determined with sufficient accuracy from the velocity field. We adopt the optical value of 22°.

UGC 5005: The inclination derived from the H I distribution is 40°, which agrees well with the 41° determined from the optical diameters.

UGC 5209: This galaxy is much smaller and much closer than the other galaxies in the sample. Inclinations derived from the H I extent are unreliable since the source is essentially unresolved (< 2 beams per major axis). The velocity range over which the H I is detected is also small (21 km s^{-1}). The total H I mass is two orders of magnitude smaller than the other galaxies, but the peak surface density is of the same order.

UGC 5750: The inclination derived from the H I distri-

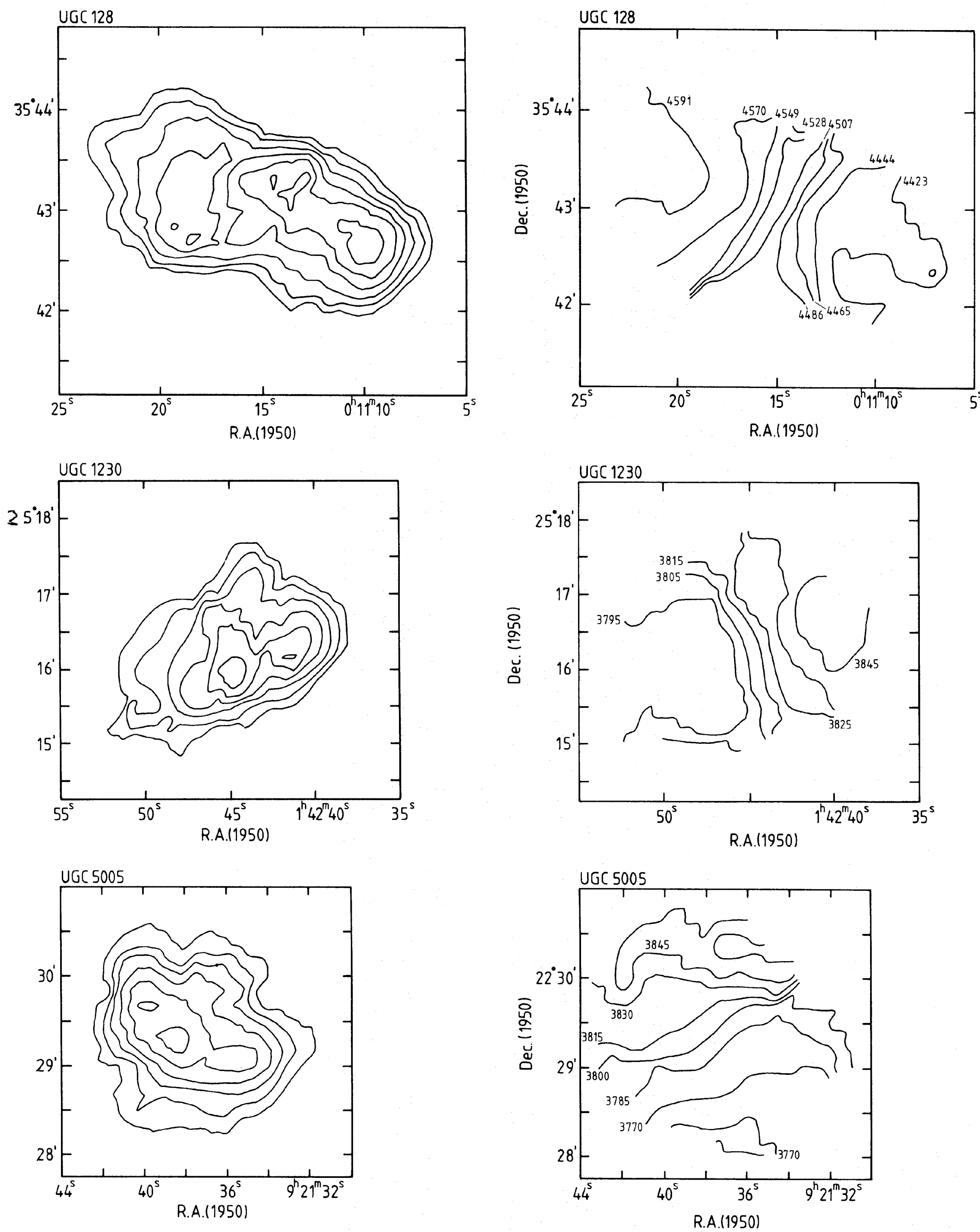

FIG. 1. H I distributions (left panels) and velocity fields (right panels) of six of the seven detected galaxies. UGC 5209 is hardly resolved and not included in this figure. The column density contours are 3, 4, 5, 6, 7, 8, 9, and 10 10^{20} atoms cm^{-2} for UGC 128, UGC 1230, UGC 5750, and UGC 5999, and 2, 3, 4, 5, 6, 7, 8, 9 and 10 10^{20} atoms cm^{-2} for UGC 5005 and UGC 6614. The hatched contour in the case of UGC 6614 denotes a local minimum. The velocity contour values are indicated in the individual velocity plots.

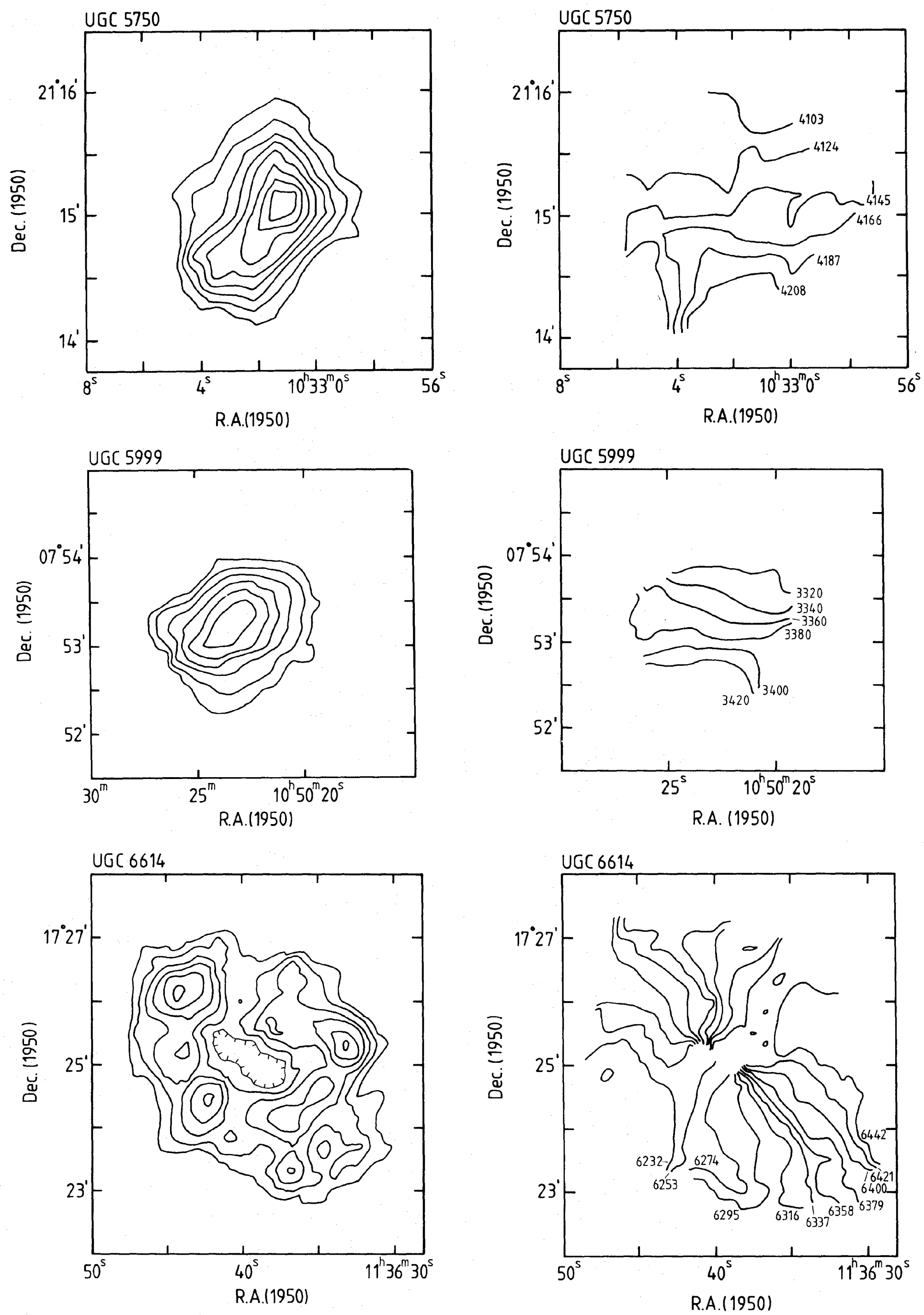

FIG. 1. (continued)

bution gave essentially the same value as the optical measurements. This galaxy is the smallest of the five galaxies at the same distance, has the lowest peak H I surface density, and the smallest flux integral. The velocity field is very asymmetric.

UGC 5999: From the H I distribution we derived an inclination of 46°. Since the galaxy is just resolved (3 beams per major axis) this value is very uncertain. We adopt the optical value of 55°.

UGC 6614: A puzzling feature of this galaxy is the misalignment between the kinematical line of nodes and the major axis of the H I distribution. The latter would suggest a major axis position angle of 45°, while the line of nodes of the velocity field has a position angle of 135°. The optical position angle (104°) is closer to the kinematical line of nodes. A warped H I layer could produce an apparent elongation, except that one always measures the greatest diameter along the kinematical major axis. Another sign of

TABLE 2. Physical properties.

	UGC 0128	UGC 0628	UGC 1230	UGC 5005	UGC 5209	UGC 5750	UGC 5999	UGC 6614
Systemic velocity (km s^{-1})	4579	-	3835	3844	565	4168	3393	6350
Distance (Mpc)	60	65	51	52	7.6	56	45	85
HI flux integral (Jy × km s^{-1})	7.4	-	9.5	4.5	1.3	1.4	3.7	11.8
Peak HI surface density (10^{20} atoms cm^{-2})	8.5	<1.1	8.6	7.3	4.6	10.5	8.7	7.5
HI diameter at 1$M_\odot$ pc^{-2} (kpc)(D_{HI})	57	-	50	42	> 3	32	29	116
Total HI mass (10^9 $M_\odot$)	6.3	-	5.8	2.9	0.02	1.0	1.8	20.1
Peak radial average ($M_\odot$ pc^{-2})	4.4	-	6.5	4.8	-	3.5	5.7	2.8
p.a. of major axis (°)	62	139	−68	46	-22	167	131	108
Optical inclination (°)	57	56	22	41	53	64	55	36
M_T (10^{10} $M_\odot$)	17	-	8.4	6.3	-	2.8	8.5	69
Disk Scale Length (R) (kpc)	6.4	4.1	4.4	4.7	0.5	3.3	4.4	8.1
Central Surface Brightness (R mag $arcsec^{-2}$)	22.4	21.5	22.5	22.6	22.3	21.8	22.5	22.5
D_{25}(R) (kpc)	30.0	25.2	21.3	21.4	2.4	19.5	20.5	47.4
Luminosity L_R (10^9 $L_\odot$)	6.4	5.9	2.6	2.9	0.05	3.0	2.7	8.8
D_{HI}/D_{25}(R)	1.9	-	2.4	2.0	-	1.7	1.4	2.5
M_{HI}/M_T	0.04	-	0.07	0.05	-	0.04	0.02	0.03
M_{HI}/L_R	1.0	-	2.2	1.0	0.4	0.4	0.7	2.3

warping in the velocity field, a changing position angle and/or inclination with radius (Bosma 1979; 1981), is not found in UGC 6614.

The inclination derived from the H I distribution is 46°, and the value from the velocity field is 20°. The optical value is 36°, closer to the inclination derived from the H I distribution. We adopt 36° as the inclination angle.

UGC 6614 is unique among the galaxies in the sample in that it is twice as far away, a factor of 2 larger than the next largest galaxy, an order of magnitude more massive, and it also has the largest flux integral. Its peak surface density, however, is only the fourth largest, and its peak radial average is the lowest, suggesting a large diffuse structure. It is also the only galaxy to show a clear central minimum. Inspection of its surface brightness profile (e.g., Fig. 2) clearly shows the presence of a bulge (which dominates the light inside the μ_B=25.0 mag $arcsec^{-2}$ isophote) so perhaps the central minimum is not unexpected.

3.2 Radial Surface Brightness Distributions

The radial surface brightness distributions, derived as described in Sec. 2, are shown in Fig. 2. Table 2 gives the derived central surface brightness for the exponential disk component and the size measured at the 25 mag $arcsec^{-2}$ isophote. All objects, except UGC 5005, UGC 5209, and UGC 5999, have excess light in the central 10″, due to a bulge or lens component. No attempt was made to fit this second component. The radial surface brightness profiles could also be used to estimate disk scale lengths. These are also given in Table 2. The scale lengths and central surface brightnesses can be compared with those found by van der Kruit (1987) for a complete sample of background disk galaxies. It is clear that our objects are genuine low surface brightness galaxies, though quite a range in disk scale lengths is covered. The most extreme is UGC 6614 with its large scale length and very low surface brightness disk. Below we comment on individual optical features in the observed galaxies.

UGC 0128: This galaxy exhibits some faint spiral structure. The surface brightness profile in unusual and not described at all by a single exponential. Instead two exponentials give the best fit. The D_{25} diameter is 103″ or 30 kpc.

UGC 0628: This galaxy has multiple spiral arms and its brightness distribution is also not well described by a single exponential. The diameter is 80″ or 25.2 kpc.

UGC 1230: The morphology of this very LSB galaxy is somewhat irregular. A single exponential fits the surface brightness profile well leaving some excess light in the central 10″. The D_{25} diameter is 86″ or 21.3 kpc.

UGC 5005: The light distribution is very peculiar and consists of an exponential disk in the outer parts which diminishes in the inner 6″. The average surface brightness does not exceed 23.2 mag $arcsec^{-2}$. The D_{25} diameter is 85″ or 21.4 kpc.

UGC 5209: The surface brightness distribution has a very flat inner part and a rapid fall off beyond 16″ radius. The diameter is 85″ or 2.4 kpc. This galaxy has a rather smooth appearance, but is irregularly shaped. It resembles the Virgo dI galaxies.

UGC 5750: The inner bright region has the appearance of a bar with incipient spiral structure at the ends. The radial brightness distribution is peculiar. The outer parts can be described by an exponential disk, but in the region between 10″ and 25″ the surface brightness drops below the extrapolated exponential disk level. The D_{25} diameter is 72″ or 19.5 kpc.

UGC 5999: This is a very irregular galaxy with some high surface brightness knots and some incipient spiral structure. Its size is 94″ or 20.5 kpc. The surface brightness profile is well fit by a single exponential disk.

UGC 6614: This galaxy has a very extended LSB disk which can be traced out to a radius of at least 130″. Its central surface brightness, although uncertain, is the lowest in the samples at $B(0)=24.3\pm0.2$. The bulge component dominates inside a radius of 15″ and is most of what one can easily distinguish of this galaxy on the Sky Survey.

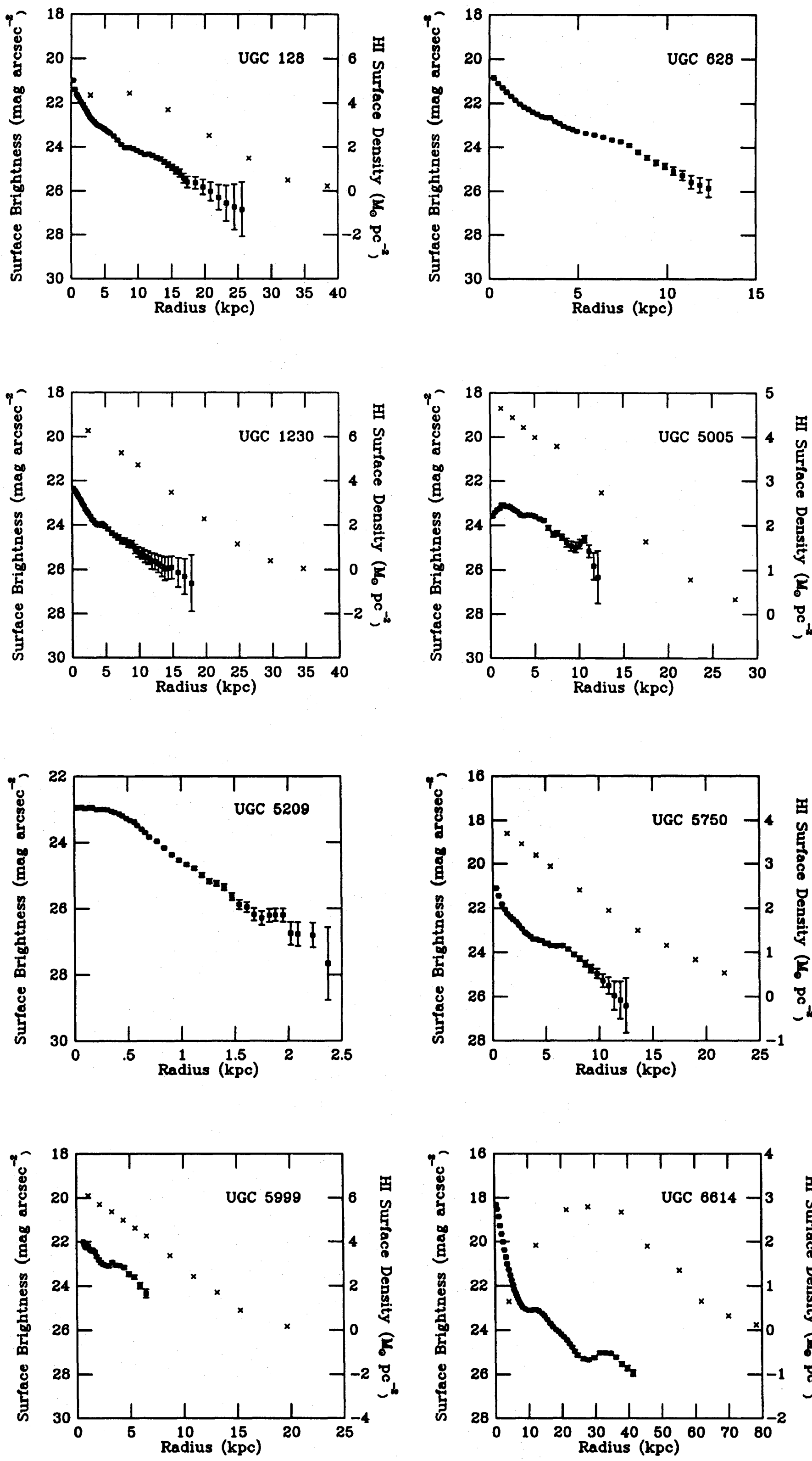

FIG. 2. Radial surface brightness distributions in *R* of all eight galaxies (filled circles) and radial H I surface density distributions of the six galaxies (crosses) shown in Fig. 1. The surface brightness scale is indicated along the left vertical axis; the H I surface density scale is indicated along the right vertical axis.

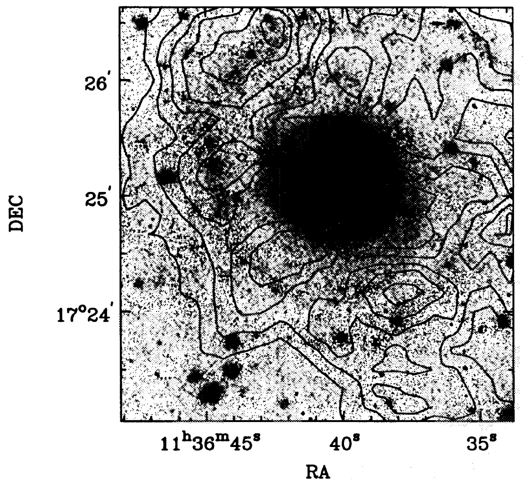

FIG. 3. Overlay of the H I surface density distribution on an Hα plus continuum image of the inner regions of UGC 6614. Contours are 2, 3, 4, 5, 6, and 7 10^{20} atoms cm^{-2}. Notice the coincidence of the outer faint spiral structure and the peaks in the H I surface density distribution.

This galaxy bears a close resemblance to Malin 1 (Bothun *et al.* 1987). D_{25} is 115″ or 47.4 kpc. Figure 3 shows an Hα image of UGC 6614 obtained at the 2.5 m Isaac Newton Telescope at La Palma. It is quite evident that the current star formation rate in the extended disk of this galaxy is quite low. Overlaid on the Hα image are the H I column density contours to show the correspondence between the H I and optical structure. It is clear that the bulge region coincides with the relative minimum in the H I surface density distribution, while the peaks in the H I distribution coincide with the extended low surface brightness disk.

3.3 Color Distributions

Color distributions in LSB disks may help further constrain theories on their evolutionary histories. Typically, those disks which define the Hubble sequence do not show strong color gradients. In contrast, as shown in van der Hulst *et al.* (1987), the giant LSB disk NGC 3883 exhibits a very strong gradient in $B-R$. This implies that the inner disk of NGC 3883 is relatively more evolved than the outer regions. Similiar behavior is observed in other giant LSB disk galaxies (e.g., Bothun *et al.* 1990; Knezek 1992) and clearly needs to be understood. In this section we briefly comment on the color distributions exhibited by our sample galaxies. A more detailed discussion of the photometry and colors will be the subject of forthcoming papers (van der Hulst & de Blok 1993b; McGaugh & Bothun 1993b). The colors of these LSB galaxies are in general strikingly blue. Though some of this is undoubtedly due to the low metallicities of these systems (McGaugh 1993), it cannot be the only effect as the color and metallicity are not well correlated [McGaugh (1992)]. It thus seems likely that the stellar population of LSB galaxies reflects a young mean age.

UGC 0128: This galaxy has an area weighted disk color

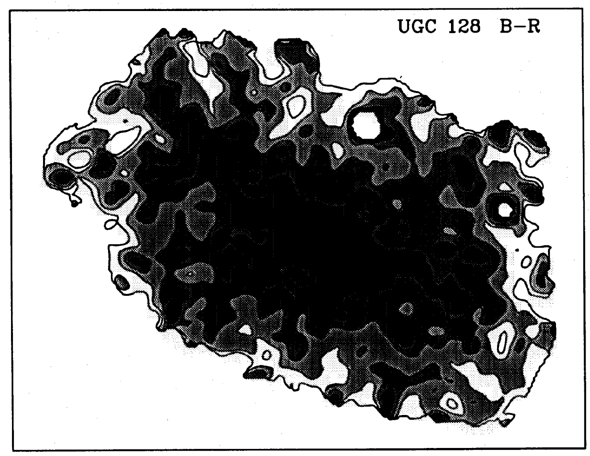

FIG. 4. $B-R$ color distribution of UGC 128. The contours are 0.4, 0.6, 0.8, 1.0, 1.2, and 1.4 in $B-R$; the corresponding grayscale intervals are 0.4-0.6, 0.6-0.8, 0.8-1.0, 1.0-1.2, and 1.2-1.4. The white area to the north–north–west of the nuclear region is an artifact caused by a bright foreground star.

of 0.49 ± 0.05 in $B-V$ and 0.02 ± 0.05 in $U-B$. The $V-I$ and $B-R$ colors are 0.55 ± 0.05 and 0.73 ± 0.05, respectively. We see a distinct radial gradient in all colors. The $B-R$ color distribution is shown in Fig. 4. Like NGC 3883, this galaxy is significantly bluer at large radii. The $V-I$ color is approximately 0.3 mag bluer than normal late-type spirals [cf. Han (1992)] and, together with the other colors, provides a strong argument that UGC 0128 has a young mean age.

UGC 0628: This galaxy is redder than UGC 0128, except perhaps in $U-B$ where we find an area weighted color of -0.07 ± 0.05. The other colors are 0.53 ± 0.05 in $B-V$, 0.86 ± 0.05 in $B-R$, and 0.78 ± 0.05 in $V-I$. Also here we see a color gradient of about 0.2 mag in all colors.

UGC 1230: This galaxy has mean disk color of 0.42 ±0.03 in $B-V$ and -0.18 ± 0.03 in $U-B$. These colors are typical of actively star forming disk systems which exhibit Hα equivalent widths of 20–25 Å. However, in this case, star formation is virtually absent. Also, its overall $V-I$ color is remarkably blue. An area weighted mean gives $V-I=0.86\pm0.04$. As in the case of UGC 0128 the colors indicate a mean young age for the disk.

UGC 6614: The colors are dominated by the bulge component and the disk is too weak to yield a reliable color. There is some indication that the disk may be quite blue. The $B-V$ and $B-I$ integrated colors of the bulge are 1.01 ± 0.03 and 2.55 ± 0.03, respectively. The integrated colors of the bulge+disk as measured interior to the $B=25.0$ mag $arcsec^{-2}$ isophote are 0.72 ± 0.05 and 2.26 ±0.07. This change in color may also reflect a metallicity gradient in the bulge since that component still dominates the light at large radii.

4. DISCUSSION

4.1 Resolution Effects

Before discussing the consequences of these observations for the evolution of LSB galaxies we will address the question of resolution effects. It is clear that lowering the resolution of the H I maps will initially decrease the peak surface densities measured because of beam dilution. Radially averaged surface densities are, however, much less susceptible to the effects of beam dilution. Radially averaged surface densities will not significantly decrease until averaged over a very large area comparable to the size of the disk. The question arises whether the resolution used here (9.7 kpc at the average distance of 50 Mpc) is in the regime where one measures the average surface density appropriately. As a test of these resolution effects, we examined the published data on the well studied galaxies M33 and M101.

For M33 we compared the radially averaged H I column density profiles from the single dish study of Gordon (1971) with the synthesis observations of Wright *et al.* (1972), Reakes & Newton (1978), Newton (1980), and Deul & van der Hulst (1987). The results of the comparison for M33 are somewhat uncertain due to its very large angular extent and the problem of accounting for flux on large angular scales in the synthesis data (see discussion in Deul and van der Hulst). On the one hand, the single dish observations of Gordon (resolution $\sim$2 kpc) show as much as 50% higher surface densities than the synthesis observations. On the other, the synthesis observations, which span a range of 30 in resolution, all produce similar measures of radially averaged H I surface density.

Given the larger distance and smaller angular size of M101, comparisons are much less subject to uncertainties concerning large scale emission and probably more appropriate for our purpose here. A comparison of the observations of Rogstad & Shostak (1971), Allen & Goss (1979), and van der Hulst & Sancisi (1988) shows that these observations are all comparable over a factor of about 10 in resolution ($\sim$0.45–4 kpc). To check further, we smoothed the integrated column density image of van der Hulst and Sancisi and measured the radially averaged H I column density profile at several values of the resolution. We found that the peak in the radially averaged distribution dropped by only 25% as the resolution was decreased from 0.5 to 17 kpc. From these exercises we feel confident that the radially averaged H I profile is a very stable parameter with which to compare galaxies, even at very different resolutions. That is, averaging over as much as 10 kpc does not significantly change the average surface density provided the gas disk of the galaxy is reasonably well resolved (>3 beams across the galaxy).

The low surface densities found for these LSB galaxies are in contrast with the quite normal integrated H I masses found (see Table 2). From the integrated H I masses one would, for example, conclude that these galaxies have normal gas contents and it is only because of their large H I sizes that the H I surface densities drop below the levels usually found in normal spiral galaxies. In part this is a selection effect caused by the low surface brightnesses of these galaxies and hence small photometric [$D_{25}(R)$] diameters: we tend to underestimate the size of low surface brightness galaxies. The large values of $D_{\rm H\,I}/D_{25}(R)$ in Table 2 clearly illustrate this point. The mean $D_{\rm H\,I}/D_{25}(B)$ found by Warmels (1986) and by Broeils (1992) for a sample of normal surface brightness galaxies is 1.8 using blue diameters. The ratio of red to blue diameters for the galaxies in our sample is about 1.3 so that our equivalent mean $D_{\rm H\,I}/D_{25}(B)$ is 2.4 compared to the 1.8 of Broeils (1992) and Warmels (1986).

The $M_{\rm H\,I}/M_T$ ratios on the other hand appear normal, albeit somewhat low, for late-type spiral galaxies. $M_{\rm H\,I}/L_R$ also has reasonably normal values with the exception of UGC 1230 and UGC 6614 which both have quite large ratios. It appears that the properties of the H I in LSB galaxies are relatively normal as also found by Schombert *et al.* (1992). The average surface density, however, is lower than in HSB galaxies as a result of the larger sizes of the H I disks. Van der Hulst *et al.* (1987) already pointed out the danger of using integral properties and the results here strongly emphasize that point.

4.2 H I Surface Densities and Star Formation Thresholds

In Fig. 2 we present the average radial H I surface density distributions of the six LSB galaxies which we could resolve reasonably well. The maximum surface densities of these distributions range from 3 to 6 $\mathscr{M}_\odot\,{\rm pc}^{-2}$ with an average of 4.6 ± 1.4 $\mathscr{M}_\odot\,{\rm pc}^{-2}$. How does this compare with normal, high surface brightness spiral galaxies? To answer this properly requires an unbiased comparison sample. Warmels (1986) found an average peak H I mass surface density of 8.7 $\mathscr{M}_\odot\,{\rm pc}^{-2}$ for the radially averaged H I distributions of normal field spirals. Recently Cayatte *et al.* (1993) have combined Warmels' field sample with new H I observations by Broeils (1992) and have compared the radially averaged H I distributions by morphological-type. Since the peak H I surface mass density varies as a function of morphological-type, it is important to choose the proper comparison. Our six LSB galaxies are all too luminous to be considered dwarfs and lack significant bulges, so Scd and Sd galaxies would appear to be the appropriate comparison galaxies. Cayatte *et al.* find average peak surface mass densities of 8.5 $\mathscr{M}_\odot\,{\rm pc}^{-2}$ for Scd galaxies and 10 $\mathscr{M}_\odot\,{\rm pc}^{-2}$ for Sd galaxies. Thus, the average peak H I surface density for the six LSB galaxies is only half that of the field galaxies. The difference becomes even larger if the other two LSB galaxies are accounted for. While there is a large dispersion from galaxy to galaxy in the field sample, the conclusion that the H I surface densities in the LSB galaxies are *on average* lower than those found in comparable high surface brightness galaxies seems secure. These new observations confirm the earlier suggestion by van der Hulst *et al.* (1987) based on H I observations of three red LSB galaxies.

The peak surface densities in the H I distributions themselves are below 10^{21} atoms ${\rm cm}^{-2}$ or 8 $\mathscr{M}_\odot\,{\rm pc}^{-2}$. This is consistent with the levels originally proposed to be a practical threshold for star formation from observations of irregular galaxies (Davis *et al.* 1976; Hunter & Gallagher 1986; Skillman 1987). Global measures of galaxies produce similar values for spirals (Guiderdoni 1987), while resolved observations prove more difficult to interpret (e.g., Wilson & Scoville 1991). The study by Kennicutt (1989) has shown the importance of including a dynamical criterion in a star formation threshold analysis and the next critical step is to compare the actually measured H I surface density with the critical density for star formation.

Since we have, albeit crude, velocity fields for at least six galaxies it is possible to estimate rotation curves and use these to calculate the critical density

$$\Sigma_c = \alpha \kappa \sigma_v / 3.36G, \quad (1)$$

with the epicyclic frequency

$$\kappa = 1.41 \frac{V}{R} \left(1 + \frac{R}{V}\frac{dV}{dR}\right)^{1/2}, \quad (2)$$

where σ_v is the velocity dispersion in the gaseous disk, and α is a constant found by Kennicutt (1989) to be 0.6. Because only a few galaxies have velocity fields sampled well enough to allow a reliable velocity field analysis we restricted ourselves to estimating rotation curves from position velocity cuts along the major axes. For these galaxies this procedure is not less accurate than a formal velocity field analysis following the procedure outlined originally by Warner *et al.* (1973). The largest uncertainty in the rotation curves actually results from the uncertain inclinations rather than the differences between our estimates from the major axis cuts and a more formal velocity field analysis. Figure 5 shows the rotation curves derived as outlined above for the six resolved galaxies. All have the slowly rising behavior characteristic of late-type galaxies (e.g., see Bosma 1979, 1981; Kent 1987; Casertano & van Gorkom 1991) and fairly moderate maximum velocities, an exception being UGC 6614 with a maximum rotation velocity of 200 km s^{-1}. The total masses estimated from the rotation curves using the outermost measured point are given in Table 2.

The critical surface density Σ_c as a function of radius given by Eq. (1) is plotted in Fig. 5 together with the measured H I surface densities. Though the uncertainties are rather large it is quite striking that the measured H I surface densities systematically fall just below the estimated critical surface densities throughout most of the disks of these LSB galaxies. In some cases, over a limited range of radii, the H I surface density does rise to meet or exceed the critical value and this is where the H II regions are generally found.

4.3 Evolutionary History of LSB Disks

The apparently low current star formation rates observed in the LSB galaxies (McGaugh 1992) are best explained by our result that the gas surface densities are below the critical density for star formation. In more general terms, it may well be that the H I surface density is insufficient for the efficient formation of giant molecular clouds. If so, then star formation which proceeds in atomic H I could well have an unusual Initial Mass Function (IMF). For instance, an IMF deficient in massive stars would help keep the enrichment of the Interstellar Medium (ISM) low. This helps to explain the rather blue colors of these disks with little or no current star formation as well as the observed low metal abundance (see also McGaugh 1992). On the other hand, some of our sample galaxies are so blue (particularly in $B-I$ or $V-I$) that a young mean age or even relatively recent formation is implied. The tendency for these disks to be deficient in molecular gas has been confirmed by Schombert *et al.* (1990) although the conversion between CO and H_2 may be different from the galactic value in these metal poor disks. The unevolved nature of these disks, relative to those similar mass disks which define the Hubble sequence, may indicate that these galaxies have been unable to sustain a healthy star formation rate for a large fraction of a Hubble time. This is in distinct contrast to normal galaxies which have supported star formation and metal enrichment to the point of nearly complete astration. Since it is quite unlikely that high surface brightness disks have all come into a phase of active star formation just recently, we strongly suspect that LSB galaxies have had low surface density gas disks for most of their existence and have hence maintained a quiescent state.

The low rate of evolution of these systems bears a striking resemblence to the low evolutionary rate which has been inferred for the space density of damped Lyman-α systems seen in various Quasi-Stellar Object (QSO) lines of sight (e.g., Steidel 1993). The inferred H I column density in many damped Lyman-α systems compares favorably with our observations as well as the estimated threshold for star formation. In fact, the only real difference between LSB disks and the damped Lyman-α systems is that some star formation has occurred in the former relative to the latter. This argues for the existence of a continuum of H I column densities which are confined in the gravitational potential of a dark halo. Above some critical column density, rapid star formation and enrichment produces the Hubble sequence. At or near the threshold for star formation, disk evolution is a sporadic and mostly quiescent process. Below another critical column density, the H I is likely to be ionized by the metagalactic UV flux (see Maloney 1990, 1992, 1993). Hence, the ultimate fate of the H I content of the Universe is not necessarily to transform itself into a conspicuous galaxy. Moreover, this range in column densities may manifest itself into a range of disk formation epochs and some LSB galaxies (e.g., UGC 0128 and UGC 1230 in our sample) would appear to have formed rather recently.

The question arises whether the inability to build up a gas disk of sufficient gas density depends on the environment or just on initial conditions. If disks form by accretion of gas rich objects (Sancisi *et al.* 1989; White & Rees 1978; Norman & Silk 1981) one expects that galaxies in areas of low galaxy density never form decent gas disks. In this case one expects to find LSB galaxies predominantly in regions of low galaxy density, i.e., lower than the regions in the universe where one finds the normal field galaxies. A recent statistical study by Bothun *et al.* (1993) shows that this is the case. In addition Zaritsky & Lorrimer (1993)

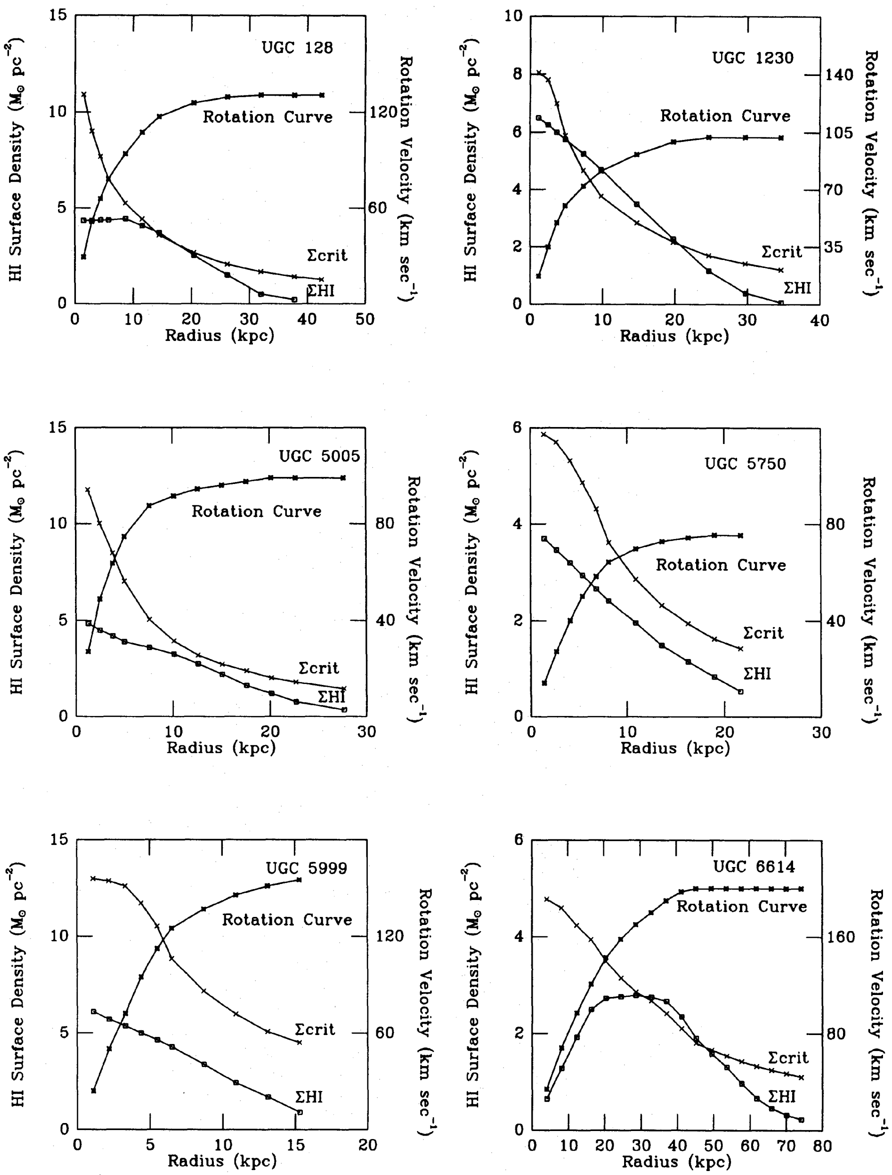

FIG. 5. Rotation curves, H I surface density distributions, and critical density distributions of the six galaxies shown in Fig. 1. The surface density scale is indicated along the left vertical axis; the velocity scale is indicated along the right vertical axis.

(1993) found that there is a paucity of companions to LSB disks, pointing at another consequence of the low galaxy density environment, i.e., less triggering of star formation by tidal encounters with nearby galaxies. Without this tidal trigger the LSB disks will remain quiescent.

5. CONCLUDING REMARKS

We have observed eight LSB galaxies with the VLA in order to map their H I surface density distributions. Six of these are sufficiently resolved that a radial surface density distribution could be measured and that an estimate of the rotation curve could be made. The highest radially averaged surface densities are about 4.5$\mathscr{M}_\odot$ pc^{-2}, a factor 0.6 below the highest radial average found in normal galaxies. The critical threshold density for star formation as formulated by Kennicutt (1989) is systematically higher than the observed H I surface densities throughout the disks of these LSB galaxies. The work of Schombert *et al.* (1990) suggests that the molecular gas content in LSB galaxies is low implying that the H I is a good measure of the total gas surface density. The systematic difference between actual and critical surface density strongly supports the idea that LSB galaxies have had inefficient or at most moderate star formation during most of their lifetimes as a result of the lack of gravitational instabilities in their gas disks which have normal sizes but too low surface densities. The lack of molecular line emission may indicate that LSB galaxies fail to form the giant molecular clouds required for massive star formation and that the low mass star formation in LSB disks progresses outside molecular clouds. Such objects then remain quiescent and inconspicuous over a Hubble time. Hence, they are excellent examples of transition objects between well formed galactic disks (e.g., those used to define the Hubble sequence) and the unevolved damped Lyman-α systems seen towards QSOs.

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