CHANDRA OBSERVATIONS OF NUCLEAR X-RAY EMISSION FROM LOW SURFACE BRIGHTNESS GALAXIES

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ABSTRACT

We present *Chandra* detections of X-ray emission from the active galactic nuclei (AGN) in two giant low surface brightness (LSB) galaxies, UGC 2936 and UGC 1455. Their X-ray luminosities are 1.8×10^{42} ergs s^{-1} and 1.1×10^{40} ergs s^{-1} respectively. Of the two galaxies, UGC 2936 is radio loud. Together with another LSB galaxy UGC 6614 (*XMM-Newton* archival data) both appear to lie above the X-ray–radio fundamental plane, and their AGN have black hole masses that are low compared to similar galaxies lying on the correlation. However, the bulges in these galaxies are well developed, and we detect diffuse X-ray emission from four of the eight galaxies in our sample. Our results suggest that the bulges of giant LSB galaxies evolve independently of their halo-dominated disks which are low in star formation and disk dynamics. The centers follow an evolutionary path similar to that of bulge-dominated normal galaxies on the Hubble sequence, but the LSB disks remain unevolved. Thus, the bulge and disk evolution are decoupled and so whatever star formation processes produced the bulges did not affect the disks.

Key words: galaxies: active – galaxies: bulges – galaxies: evolution – galaxies: individual (UGC 2936, UGC 1455) – X-rays: galaxies

Online-only material: color figures

1. INTRODUCTION

Low surface brightness (LSB) galaxies are poorly evolved systems that have diffuse stellar disks, large H I disks, and massive dark halos (Impey & Bothun 1997). The dark halo inhibits the growth of disk instabilities such as bars and spiral arms; this leads to an overall poor star formation rate over these galaxies (Boissier et al. 2008; O'Neil et al. 2007). As a result, LSB galaxies are metal poor (Kuzio de Naray et al. 2004) and optically dim. Optical studies show that they span a wide range of morphologies from dwarfs to giant spirals (Beijersbergen et al. 1999). Our paper focuses on giant LSB spirals which are characterized by prominent central bulges, optically dim disks and extended H I gas disks, a good example being Malin 1 (Barth 2007; Impey & Bothun 1989). These galaxies are also fairly isolated systems (Rosenbaum & Bomans 2004). The origin and evolution of these galaxies are still unclear; one possibility is that they form in low-density environments and hence remain unevolved (Hoffman et al. 1992).

Although LSB galaxy disks have been studied at length at optical and infrared wavelengths (Burkholder et al. 2001; Rahman et al. 2007; Hinz et al. 2007), not much is known about their nuclear properties. In particular, their nuclear black hole (BH) masses and AGN–bulge evolution history remain largely unconstrained. Optical spectroscopy indicates that a significant fraction have active galactic nuclei (AGNs; Sprayberry et al. 1995) and large bulges (Schombert 1998). Nuclear activity has also been detected at radio wavelengths (M. Das et al. 2009, in preparation). However, the best way to detect and study AGN activity is using X-ray emission which will give rise to a compact X-ray bright source at the galaxy nucleus. There may also be a primordial X-ray-emitting gaseous halo which will appear as diffuse X-ray emission associated with the galaxy or its bulge. Very little is known about BH masses in bulge-dominated LSB

galaxies, but indirect studies suggest that it is low compared to normal galaxies (Pizzella et al. 2005). This raises interesting questions regarding the evolution of BHs, AGN, and bulges in poorly evolved and isolated galaxies. In this paper, we examine these issues with observations made using the *Chandra* X-ray Observatory. Essentially, nothing is known about the X-ray properties of LSB galaxies (possibly because the lack of star formation and, hence, the low number of high-mass X-ray binaries suggests low X-ray emission). In the following sections, we present the results of a pilot study of eight giant LSB galaxies with *Chandra* and discuss the implications of our observations.

2. OBSERVATIONS

2.1. Sample Selection

We observed a total of eight LSB galaxies with *Chandra* during Cycle 8. Our sample is based on a sample of gas rich, predominantly low surface brightness galaxies with optical AGN defined by Schombert (1998). We have not independently quantified their LSB characteristics with photometric observations. Although a few galaxies (such as UGC 12845) are clearly LSB, surface photometry is required to establish the LSB nature of the entire sample. Our sample was also limited by the fact that we had only 30 ks of observing time. Hence, only a few nearby, giant LSB galaxies were chosen. Thus, our sample is by no means complete but does give a first look at the X-ray properties of these galaxies. All the galaxies are large, H I rich and nearby; they are derived from the UGC catalogue ($v_{sys} \leqslant 15,0000$ km s^{-1}). We chose a subset of eight nearby ($v_{sys} \leqslant 10,000$ km s^{-1}) optically active LSB galaxies from this sample in order to maximize our chances of X-ray detection with *Chandra*. Thus, all the eight galaxies in our sample have prominent bulges and optically identified AGN. In the following paragraph, we give a brief description of each galaxy. We take

low surface brightness galaxies to have central surface brightness > 22 mag arcsec^{-2}, which is clearly below the Freeman value.

UGC 1455: The galaxy has a disk *B*-band brightness of 22.4 mag arcsec^{-2} (Graham 2003). At the center of the LSB disk is a prominent bulge which is oval in shape and may represent a small bar (de Jong 1996).

UGC 2936: This is a fairly inclined galaxy with an LSB disk fainter than 22 mag arcsec^{-2} (Sprayberry et al. 1995) and a very extended H I disk. So it falls into the LSB category but has significant star formation over the disk which is unusual for a LSB galaxy (Pickering et al. 1999).

UGC 1378: This galaxy is classified as an LSB galaxy by Schombert (1998); it has a prominent bulge but diffuse disk. Deeper photometry of the galaxy in the literature is lacking.

UGC 1922: The galaxy has a prominent nucleus but a very featureless LSB disk; appearance is indicative of a giant LSB galaxy based on Schomberts classification. Deeper photometry of this galaxy is lacking. It is one of the few LSB galaxies that have been detected in CO emission signifying the presence of molecular gas (O'Neil & Schinnerer 2003).

UGC 3059: This is a fairly inclined galaxy like UGC 2936 and is classified as an LSB galaxy by Schombert (1998). It has a prominent bulge, diffuse stellar disk and large H I gas disk.

UGC 4422: Also known as NGC 2595, this galaxy has a disk *B*-band brightness of 22.14 mag arcsec^{-2} (Graham 2003) and so falls into the LSB galaxy category. The galaxy has a bright core, small bar, and prominent spiral arms. However, the disk shows signs of ongoing star formation which is unusual for LSB galaxies.

UGC 11754: The only LSB classification for this galaxy is by Schombert; deeper photometry is lacking in the literature. However, it does have a very diffuse stellar disk similar to that seen in typical LSB galaxies.

UGC 12845: This galaxy is classified as an LSB galaxy by (Bothun et al. 1985) and also by (Graham 2003), who measure the disk brightness as 22.77 mag arcsec^{-2}. It has a prominent bulge, faint spiral arms, and a fairly diffuse stellar disk.

2.2. Chandra Observations and Data Reduction

This was a pilot study, and the total time of the observation was 30 ks. The galaxies and their observation IDs are listed in Table 1 along with the exposure time. All the observations were performed with the Advanced CCD Imaging Spectrometer (ACIS) with the aimpoint placed on chip-S3 of the ACIS-S array.
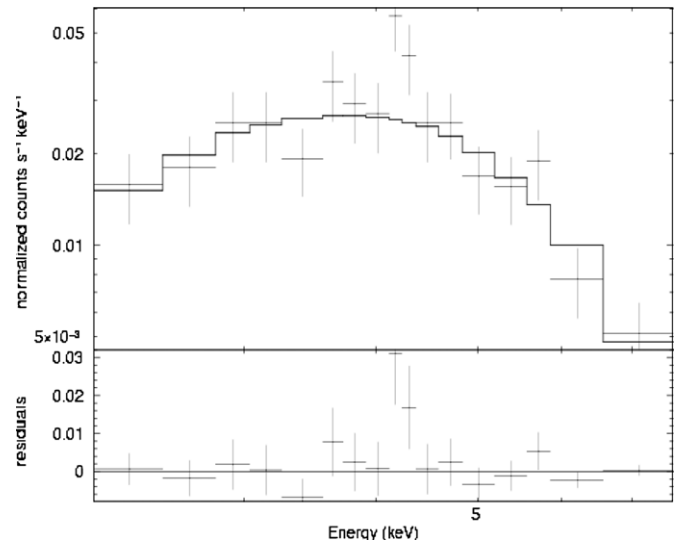
Figure 1. X-ray spectrum of the emission from the nucleus of UGC 2936, binned in the energy range 0.5–10 keV. The corresponding fit is overlaid.

The data were reduced according to the standard threads using CIAO version 3.4 and all spectral analysis was performed with XSPEC version 12.2.1.

3. ANALYSIS AND RESULTS

3.1. Nuclear Sources

For each galaxy, we began by using the `wavdetect` source detection algorithm to search for any compact/pointlike emission associated with the nucleus; such emission would be a signature of AGN activity. We detected a compact source in the center of two galaxies in our sample, UGC 2936 and UGC 1455.

For UGC 2936, the photon count rate was sufficient to extract a spectrum. The spectrum was extracted using the CIAO script `psextract`, and grouped to have 15 counts per bin in order to permit the use of χ^2 statistics (Figure 1). The 0.5–10 keV spectrum was fitted with a model consisting of a power law and modified by photoelectric absorption from cold line-of-sight gas. Including only the Galactic absorption ($N_H = 1.24 \times 10^{21}$ cm^{-2}) gave a poor fit and a very flat photon index ($\chi^2/dof = 59/16$ and $\Gamma = -1.2$). The fit improves dramatically ($\chi^2 = 14.2/15$) if we allow for additional absorption, presumably associated with UGC 2936 itself; the best fitting model has a total absorbing column $N_H = (5.3^{+2.2}_{-1.6}) \times 10^{22}$ cm^{-2} and photon index $\Gamma = 1.14^{+0.72}_{-0.63}$ (90% confidence level for one free parameter is quoted). Figure 2 shows the confidence contours

Table 1
Galaxy Sample and X-ray Fluxes

Galaxy name	Distance (Mpc)	Galaxy position RA, δ (J2000)	Observation ID	Exposure time (Ks)	AGN luminosity (erg s^{-1})	Diffuse gas luminosity (erg s^{-1})	Mid-IR flux (erg cm^{-2}s^{-1})
UGC 1455	67.3	01^{h}58^{m}48^s.0, +24°53′33″	7764	3.79	1.1×10^{40}	5.5×10^{39}	$< 2.0 \times 10^{-11}$
UGC 2936	51.2	04^{h}02^{m}48^s.2, +01°57′57″	7769	2.74	1.8×10^{42}	7.5×10^{40}	7.3×10^{-11}
UGC 1378	38.8	01^{h}56^{m}19^s.2, +73°16′58″	7763	3.45	$< 6.4 \times 10^{38}$	1.4×10^{39}	4.3×10^{-11}
UGC 1922	150.0	02^{h}27^{m}45^s.8, +28°12′33″	7884	5.88	$< 5.7 \times 10^{39}$	1.4×10^{40}	...
UGC 3059	65.8	04^{h}29^{m}42^s.4, +03°40′55″	7765	3.34	$< 1.9 \times 10^{39}$	...	1.8×10^{-11}
UGC 4422	63.4	08^{h}27^{m}42^s.0, +21°28′44″	7766	2.94	$< 1.0 \times 10^{39}$	...	$< 2.7 \times 10^{-11}$
UGC 11754	62.6	21^{h}29^{m}31^s.5, +27°19′17″	7767	4.15	$< 7.0 \times 10^{38}$	...	,,,
UGC 12845	63.9	23^{h}55^{m}41^s.9, +31°53′59″	7768	3.25	$< 1.8 \times 10^{39}$	...	...
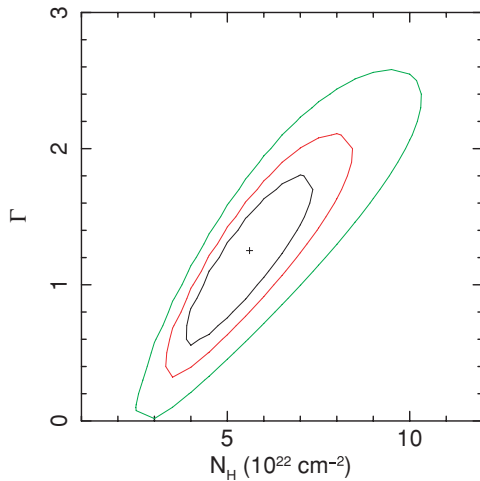
Figure 2. Confidence contours (at the 68%, 90%, and 99% confidence level for two interesting parameters) for the absorbed power-law fit to the 0.5–10 keV fit to UGC 2936.

(A color version of this figure is available in the online journal.)

on the (N_H, Γ) plane. While the best-fitting photon index is rather flatter than typical AGN (Winter et al. 2008), the typical value of $\Gamma = 1.8$ lies within the 90% error range. The source is clearly highly absorbed, however, with a 90% lower limit of 3.7×10^{22} cm^{-2} to the total absorbing column. This implies a lower limit to the *intrinsic* absorbing column in UGC 2936 of 2.5×10^{22} cm^{-2}, and is consistent with this sources classification as a Seyfert-2 galaxy (Véron-Cetty & Véron 2001). Correcting for the absorption, the 0.5–10 keV luminosity of the best fitting model is 1.8×10^{42} erg s^{-1}. The 0.5–10 keV luminosity of the best fitting model with the photon index frozen at $\Gamma = 1.8$ is 2.5×10^{42} erg s^{-1}.

In the case of UGC 1455, there were not enough counts to produce a meaningful spectrum. Instead, we used the PIMMS package to convert the count rate derived from wavdetect into a 0.5–10 keV luminosity, assuming a power-law spectrum with $\Gamma = 2$ and only Galactic absorption; the derived luminosity is 1.1×10^{40} erg s^{-1}.

For both of these objects, the compact emission coincides with the 2MASS galaxy centers, lending further support to the notion that this is AGN emission. Indeed, both of these objects have optically identified AGN emission lines (Schombert 1998). The corresponding X-ray luminosity of the AGN in UGC 2936 is comparatively high, L_x(0.5–10 kev) $\sim 1.8 \times 10^{42}$ erg s^{-1}

(Table 1) and comparable to the bright nearby Seyfert galaxies that show strong optical emission lines (Heckman et al. 2005). UGC 1455 has a comparatively lower AGN luminosity L_x(2–10 kev) $\sim 10^{40}$ erg s^{-1}, but is still bright compared to nearby low luminosity AGNs (LLAGNs) such as NGC 4303, which has a luminosity of $L_x \sim 10^{39}$ erg s^{-1} (Jiménez-Bailón et al. 2003).

For the galaxies that did not show X-ray emission from the nucleus, we used the lowest count rates of sources in the center of the field of view to derive upper estimates of AGN luminosities. We again used the CIAO program PIMMS to determine the X-ray flux values from which we derived upper limits of the X-ray luminosities. These limits are in the range L_x(0.5–10 kev) $\sim 5 \times 10^{38}$ to 5×10^{39} erg s^{-1} and are quoted on an object-by-object basis in Table 1. This luminosity is comparable to the X-ray luminosities of nearby LLAGNs which have $L_x \sim 10^{39}$–10^{40} erg s^{-1} (Ho et al. 2001). Hence, it is possible that the nondetections in our sample are a result of the galaxies being LLAGNs that are at large distances (Table 1).

3.2. Extended Emission

We searched for diffuse X-ray emission in the galaxies. Point sources were located using wavdetect. Elliptical regions around the sources were masked out and then filled based on the local background emission using the tool dmfilth. We finally smoothed the images using the routine aconvolve. This procedure gives detections of diffuse emission from four galaxies: UGC 1378, UGC 1455, UGC 1922, and UGC 2936; in all four cases, the emission is associated with the galaxy center and mostly confined to the bulge (see Figure 3 which overlays X-ray contours on the 2MASS K-band images). The emission is weakest for UGC 1455 which has only a small pool of diffuse gas.

We made approximate estimates of the diffuse gas flux and luminosity using specextract. The spectra were extracted from the galaxy centers and then examined using XSPEC. The count statistics was poor and hence the fits only approximate. But we were able to obtain a first estimate of the diffuse gas luminosities in the centers of the galaxies (Table 1). For both UGC 1455 and UGC 2936, we detected a nuclear component (AGN) as well as diffuse emission. The emission in UGC 2936 is clearly nonsymmetric about the galaxy center. Its origin may be disk star formation, or inverse Compton emission from a radio lobe. Deeper observations are required to spectrally distinguish between the two possible origins.
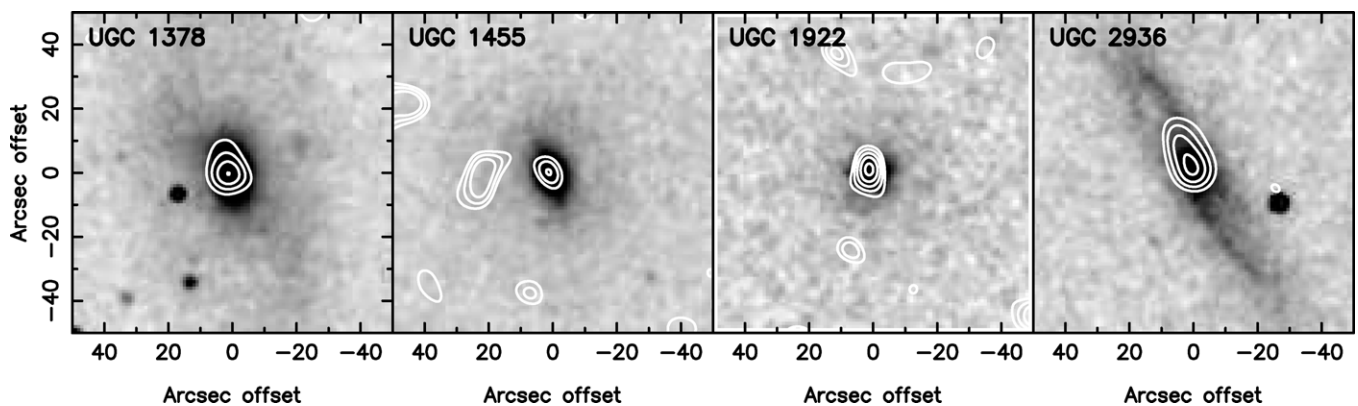
Figure 3. Contours of diffuse emission superimposed over the 2MASS near-infrared images of the galaxies UGC 1378, UGC 1922, and UGC 2936. The contours are 8, 9, 10, and 11 times the noise level for UGC 1378, UGC 1922, and UGC 2936. For UGC 1455 the contours are 9, 9.5, and 10.
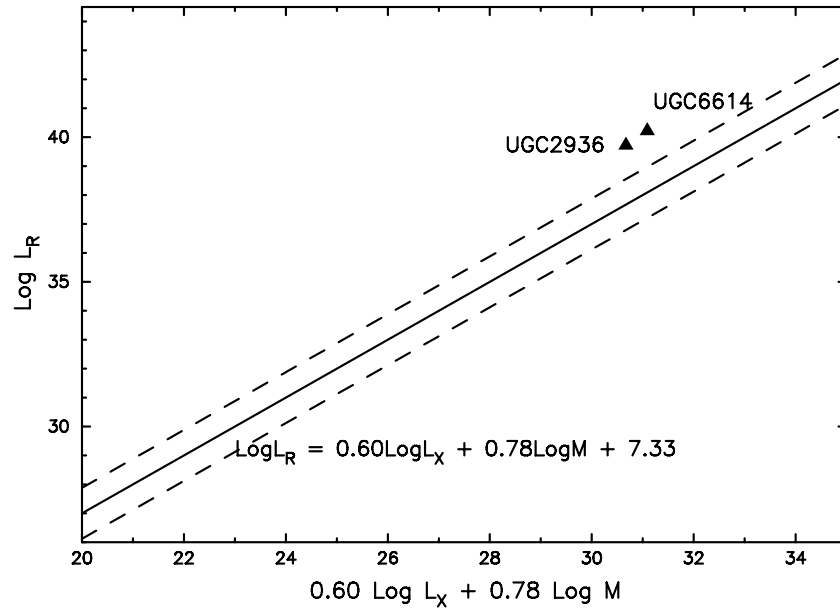
Figure 4. Plot of the radio luminosity (L_R) against the X-ray luminosity (L_x) and BH mass (M). Both L_R and L_x are in erg s^{-1} and M in solar units ($M_\odot$). The solid line marks the fundamental plane of BH activity and the dashed line is the approximate error width (Merloni et al. 2003). The errors for both UGC 2936 and UGC 6614 on either axes is much less than unity. Hence, both galaxies lie well above the plane of BH activity.

4. DISCUSSION

1. *X-ray bright AGN in LSB galaxies.* The detection of X-ray emission from the nuclei of UGC 2936 and UGC 1455 shows that though LSB galaxies are metal poor and have little ongoing star formation, their nuclei can host AGN activity that is bright in the X-ray domain. Another prominent LSB galaxy whose X-ray flux has been derived is UGC 6614 (S. Naik et al. 2009, in preparation). It has an X-ray luminosity of $L_x \sim 1.3 \times 10^{42}$ erg s^{-1} which is comparable to that observed from UGC 2936 (Table 1). Thus, the nuclear X-ray luminosity of UGC 1455 is comparable to that observed from the centers of low luminosity AGNs, but the X-ray luminosities of both UGC 2936 and UGC 6614 are comparable to bright Seyfert nuclei. About 20% of LSB galaxies show signs of AGN activity at optical wavelengths (Impey et al. 2001), which is similar to late-type spirals (Sc-Sm) for which only about 15% show AGN activity (Ho 2008). A large fraction are also radio loud (Das et al. 2006, 2007). In our sample, excluding UGC 1455 and UGC 12845, the remaining galaxies are all radio loud (NVSS survey; Condon et al. 1998), and the morphology is often a compact core with some associated extended emission representing perhaps radio lobes or jets from the AGN (M. Das et al. 2009, in preparation). Such a high fraction of radio cores are also detected in Seyferts and LINERs (Ho 2008). Thus, AGN activity in LSB systems is fairly similar to that seen in nearby Seyfert galaxies or LINERS, even though the disk morphology and star formation rate are very different from regular star forming galaxies on the Hubble Sequence.

2. *Black hole masses.* The clue to nuclear activity in giant LSB galaxies maybe the dominant bulge that is often observed in these galaxies (Schombert 1998). AGNs are more frequently found in bright galaxies with large bulges (Ho et al. 1997), and their formation and growth is linked to the mass of the supermassive black hole M_{BH} (SMBH) (Ferrarese & Ford 2005). To get an idea of the BH masses in LSB galaxies, we applied the virial technique to the AGN line emission observed from these galaxies. This method gives only an approximate estimate of M_{BH} as the emission lines could be broadened by nongravitational effects. The M_{BH} can be derived from the Hα line luminosity and linewidth (Greene & Ho 2007). Unfortunately, the relevant optical data are not available for most LSB galaxies, nor are these galaxies defined on the $M_{BH}-\sigma$ relation through other observations. Hence, we were able to derive M_{BH} for only two galaxies: UGC 2936 and UGC 6614, using published Hα line luminosities and linewidths (Sprayberry et al. 1995; Schombert 1998; Kennicutt 1984). For UGC 2936 $M_{BH} = 6.5 \times 10^6 M_\odot$ and for UGC 6614 $M_{BH} = 2.9 \times 10^7 M_\odot$. We then used the X-ray luminosities (see Table 1 for UGC 2936 and for UGC 6614 $L_x \sim 1.3 \times 10^{42}$ erg s^{-1}) and the radio luminosities (L_R) of these galaxies to see where they lie on the L_X-L_R fundamental plane (Merloni et al. 2003). For UGC 2936, we used Giant Metrewave Radio Telescope observations at 610 MHz and 1280 MHz to determine the radio spectral index ($\alpha = 0.55$) and then derived the L_R at 5 GHz. For UGC 6614, since the spectral index is flat, we used the flux density in the VLA 1.4 GHz map to derive L_R at 5 GHz (Das et al. 2006). We find that both galaxies lie surprisingly well above the L_X-L_R plane, and their M_{BH} values are considerably lower than galaxies lying on the correlation as shown in Figure 4. Thus, though these LSB galaxies show AGN activity comparable to normal Seyferts, their nuclear black holes appear to be less massive than those detected in brighter galaxies.

3. *Diffuse emission from the bulge.* This is the first tentative detection of diffuse X-ray emission from LSB galaxies. Such emission may arise from massive star forming regions and supernovae (Cui et al. 1996; Strickland & Heckman 2007; e.g. M82), coronal X-ray emitting gas from galactic fountains (Fraternali & Binney 2008) or star formation in spiral arms (Tyler et al. 2004) and is thus associated with metal enrichment in galaxies. In the galaxies UGC 1378

and UGC 1922, the diffuse gas is mainly concentrated in the bulge (Figure 3). For UGC 1455, it is associated with the bulge and the small, oval bar in the center, which may alternatively be a pseudobulge (de Jong 1996). In UGC 2936, the emission is concentrated in the bulge but also extended on one side (see item 4, this section). Since there is no apparent ongoing star formation activity in any of the galaxies except UGC 2936, which shows patchy $H\alpha$ emission over the disk and nucleus (Robitaille et al. 2007), the most likely origin for the diffuse emission is the old stellar population in the bulges as well as AGN activity in the center of these galaxies. The luminosity is 10^{36}–10^{40} erg s^{-1} which is similar to that observed from the centers of nearby spiral galaxies (Tyler et al. 2004). We also determined the mid-infrared emission (at 12 μm) for five galaxies in our sample; these were all *Infrared Astronomical Satellite* values from the NASA/IPAC Extragalactic Database (Table 1). The mid-IR flux values are similar to that observed from the centers of nearby bright galaxies in Tyler et al. (2004). This further supports the idea that the diffuse emission arises from star formation associated with the bulge.

4. *Diffuse emission extending into the disk in UGC 2936.* The diffuse emission in UGC 2936 clearly extends out into the disk on one side of the galaxy center in the northeast direction (Figure 3). The simplest interpretation is spiral arm star formation. However, we do not detect similar emission from the other side. The asymmetry suggests that we cannot rule out an X-ray jet origin for the emission; the jet may be associated with the strong AGN activity in the galaxy. Further observations are required to understand this interesting feature.

5. *Bulge evolution independent of disk evolution?* Our observations show that LSB galaxies host AGN and relatively massive black holes despite having poorly evolved disks. They are similar to bulgeless late-type spirals in their disk properties (Böker et al. 2002) but closer to bulge-dominated galaxies in their nuclear properties. Thus, the disks and nuclei of these galaxies may have evolved fairly independently of each other. One of the reasons for this kind of evolution could be the shape of the dark halo potential in LSB galaxies. The halo potential is found to be relatively shallow in the center or bulge (Kuzio de Naray et al. 2008; Zackrisson et al. 2006) but relatively strong in the disk. This would allow the center to evolve, whereas disk instabilities would be suppressed by the presence of the dark matter halo at larger radii (Mihos et al. 1997). Alternatively, the bulges may have evolved through other processes such as galaxy collisions (Mapelli et al. 2008); however, the disks in such processes have to remain fairly undisturbed which is a tough constraint for such models. Another process could be the slow secular evolution of the disk through the formation of oval distortions or pseudobulges (Kormendy & Kennicutt 2004). The latter process is more likely as some giant LSB galaxies are found to have photometric signatures of pseudobulges (Pizzella et al. 2008). Overall these galaxies represent a good example of decoupled bulge–disk evolution and the underlying processes should be investigated in more detail.

5. CONCLUSIONS

We present *Chandra* observations of eight giant, LSB galaxies all of which have a sizable bulge. Our main results are as follows.

1. We have detected compact X-ray emission from the nuclei of two LSB galaxies, UGC 1455 ($L_X = 1.1 \times 10^{40}$ erg s^{-1}) and UGC 2936 ($L_X = 1.8 \times 10^{42}$ erg s^{-1}); it is due to AGN activity in these galaxies. The AGN emission is similar to that observed from the centers of nearby Seyfert and LINER galaxies.

2. For the galaxies UGC 2936 (our sample) and UGC 6614 (*XMM-Newton* archival data), we combined X-ray luminosities with radio luminosities and BH masses to determine the location of these galaxies on the radio–X-ray fundamental plane. We find that both galaxies lie above the plane which suggests that their nuclei harbor less massive black holes compared to normal galaxies on the plane.

3. Diffuse X-ray emission was detected from the bulges of four galaxies. The luminosity is similar to that observed from the centers of nearby star forming galaxies. These results combined with AGN emission suggest that the AGN and bulges of LSB galaxies have followed an evolutionary path similar to bulge-dominated bright galaxies even though their LSB disks are poorly evolved.

4. The detection of AGN and diffuse emission from the bulges of LSB galaxies shows that galaxies with unevolved disks can have normal bulges. Thus, whatever star formation processes made the bulge did not make the disk component in these galaxies. In fact the bulge and disk evolution appears to be distinctly decoupled in these galaxies. Giant LSB galaxies are thus good sites to study decoupled bulge–disk evolutionary processes.

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