Active galactic nucleus activity and black hole masses in low surface brightness galaxies

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ABSTRACT

We present medium resolution optical spectroscopy of a sample of nine low surface brightness (LSB) galaxies. For those that show clear signatures of active galactic nucleus (AGN) emission, we have disentangled the AGN component from stellar light and any Fe I and Fe II contribution. We have decomposed the He II line into narrow and broad components and determined the velocities of the broad components; typical values lie between 900 and 2500 km s$^{-1}$. Of the galaxies in our study, UGC 6614, UGC 1922, UGC 6968 and LSBC F568−6 (Malin 2) show clear signatures of AGN activity. We have calculated the approximate black hole (BH) masses for these galaxies from the He II line emission using the virial approximation. The BH masses are $\sim 3 \times 10^5$ M$_\odot$ for three galaxies and lie in the intermediate-mass BHs domain rather than the supermassive range. UGC 6614 harbours a BH of mass $3.8 \times 10^6$ M$_\odot$; it also shows an interesting feature bluewards of He II and H$\beta$ implying outflow of gas or a one-sided jet streaming towards us. We have also measured the bulge stellar velocity dispersions using the Ca II triplet lines and plotted these galaxies on the $M$−$\sigma$ plot. We find that all the three galaxies UGC 6614, UGC 6968 and F568−6 lie below the $M$−$\sigma$ relation for nearby galaxies. Thus, we find that although the bulges of LSB galaxies may be well evolved, their nuclear BH masses are lower than those found in bright galaxies and lie offset from the $M$−$\sigma$ correlation.

Key words: galaxies: active – galaxies: bulges – galaxies: general – galaxies: nuclei.

1 INTRODUCTION

Low surface brightness (LSB) galaxies are an extreme class of late-type spiral galaxies (Impey & Bothun 1997). They are poor in star formation (O’Neil et al. 2004; Boissier et al. 2008), have low metallicities (McGaugh 1994) and low dust masses (Hinz et al. 2007; Rahman et al. 2007). However, they are gas rich (H I) and their H I discs are far more extended than their diffuse stellar discs (O’Neil et al. 2004). Their discs have weak spiral arms and their bar perturbations are not as prominent as those seen in bright galaxies. This low level of disc activity can be attributed to the presence of dark matter haloes (de Blok et al. 2001) that tend to prevent the formation of disc instabilities (Mihos, McGaugh & de Blok 1997; Mayer & Wadsley 2004; Galaz et al. 2011). Surveys show that although LSB galaxies are common in our local Universe they are preferentially found in low-density environments (Rosenbaum et al. 2009) and can have widely varying morphologies; starting from the populous dwarf LSB galaxies (Schombert, McGaugh & Eder 2001) to the giant LSB (GLSB) galaxies, of which Malin 1 is a good example (Pickering et al. 1997).

Although a lot of work has been done towards understanding the stellar and gas content of LSB galaxies, not much is known about their nuclear activity or central black hole (BH) masses. A significant fraction of GGLSB galaxies have active galactic nuclei (AGN) that are often associated with massive bulges (Schombert 1998; Impey, Burkholder & Sprayberry 2001). The AGN may be radio-bright (Das et al. 2009a) and visible at X-ray wavelengths as well (Das et al. 2009b; Naik et al. 2010). It is now well established that the BH masses in galaxies are correlated with their bulge velocity dispersions ($M$−$\sigma$) and bulge luminosities ($M$−$L$) (Ferrarese & Merritt 2000; Gebhardt et al. 2000) which suggests that BH formation, galaxy evolution and AGN activity are all interlinked (Merloni & Heinz 2008; Somerville et al. 2008; Schawinski et al. 2010). However, the $M$−$\sigma$ and $M$−$L$ relations show less scatter when only ellipticals and early-type galaxies are included (Graham 2008a,b; Hu 2008; Gültekin et al. 2009). Late-type spirals introduce more scatter in the correlations which create the need for newer calibrations of $M$−$\sigma$ and $M$−$L$ (Graham et al. 2011) as better estimates of BH masses at the low mass end are available. This may be due to a larger intrinsic scatter in the BH masses of late-type spirals or simply...
measurement uncertainties since late-type spirals, in general, have smaller bulges. They also show weaker AGN activity compared to the earlier type galaxies (Ho 2008). Alternatively, in a study by Beifiori et al. (2009) involving Hubble Space Telescope (HST) observations of 105 nearby galaxies spanning a wide range of Hubble types from ellipticals to late-type spirals, the estimated BH masses' upper limits appear to lie closer to the expected BH masses in the most massive elliptical galaxies with values of $\sigma$ above 220 km s$^{-1}$ than for galaxies with $\sigma$ in the range 90–220 km s$^{-1}$, which appears to be consistent with a co-evolution of supermassive BHs (SMBHs) and galaxies driven by dry mergers.

It is not clear where LSB galaxies lie on the $M-\sigma$ plot. Their bulge velocity and disc rotation speeds suggest that they lie below the $M-\sigma$ correlation for bright galaxies (Pizzella et al. 2005). X-ray studies also suggest that GLSB galaxies do not lie on the radio–X-ray correlation (Das et al. 2009b) and their BH masses may be quite low (Naik et al. 2010). In this paper, we use detailed optical spectroscopy to determine the position of a sample of LSB galaxies on the $M-\sigma$ diagram. We observed the nuclear spectra of several bulge-dominated LSB galaxies; for galaxies that showed AGN emission, we estimated both the BH masses and also the bulge velocity dispersion. In the following sections, we present our observations, the results and discuss the implications of our findings.

2 SAMPLE SELECTION

Our sample consists of nine large, bulge-dominated LSB galaxies from Schombert & Bothun (1987), of which eight have been observed further by Schombert (1998). The basic parameters of the galaxies are listed in Table 1. The LSB galaxies in the Schombert sample were all H$I$ rich, giant, spiral galaxies that were derived from the uppasala general catalogue (UGC) catalogue; they have systemic velocities that are less than 15 000 km s$^{-1}$. We chose a subset of eight nearby galaxies from that sample that had $v_{sys} \leq 10 000$ km s$^{-1}$ and appear to be bulge-dominated galaxies with LSB discs. The last galaxy in our list, F568–6 (or Malin 2), has been observed by Sprayberry et al. (1995) and is also bulge-dominated. The properties of individual galaxies are summarized below.

UGC 1378. This galaxy has a prominent bulge and a diffuse stellar disc. It is classified as an LSB galaxy with an active nucleus by Schombert (1998). The bulge shows diffuse X-ray emission, possibly associated with an old stellar population (Das et al. 2009b).

UGC 1922. The galaxy has a featureless disk and a bright bulge that also shows diffuse X-ray emission. It is classified as an LSB galaxy with an active nucleus by Schombert (1998). UGC 1922 is also one of the few LSB galaxies that have a significant concentration of molecular gas (O’Neil & Schinnerer 2003).

UGC 3968. Not much is known about this LSB galaxy except that it has a prominent bulge with a faint disc. The Two Micron All Sky Survey image reveals a bar associated with the bulge and two faint spiral arms. It is also classified as an LSB galaxy by Schombert (1998), but it is not clear whether the galaxy has an AGN.

UGC 4219. Not much is known about this GLSB galaxy either. According to Schombert (1998), the galaxy has a large bulge and an AGN. The LSB disc shows faint spiral arms.

UGC 6614. This is a well-studied GLSB galaxy (de Blok, van der Hulst & Bothun 1995a). It is close to face-on in morphology and has a large bulge surrounded by a ring-like feature (Hinz et al. 2007; Rahman et al. 2007). The disc has faint but tightly wound spiral arms (Pickering et al. 1997). The bulge hosts an AGN that is bright at optical (Schombert 1998), radio (Das et al. 2006) and X-ray (Naik et al. 2010) wavelengths.

UGC 6754. This galaxy has an LSB disc (Schombert & Bothun 1987) and a prominent bulge but does not appear to have an AGN (Schombert 1998). The disc has flocculent spiral arms and only patchy star formation (Amram et al. 1994).

UGC 6968. Not much is known about this galaxy, but it is described as an LSB galaxy having a prominent bulge and an AGN (Schombert 1998). There are two faint spiral arms extending out into the disc.

UGC 7357. This galaxy has an LSB disc (MacArthur, Courteau & Holtzman 2003) and a bright bulge, but does not appear to have an AGN (Schombert 1998). The disc is fairly featureless.

F568–6 (Malin 2). This is also a relatively well-studied GLSB galaxy. It has an LSB disc (Schombert & Bothun 1987), prominent bulge and an AGN (Schombert 1998). Like UGC 1922, it is one of the rare LSB galaxies that have a significant mass of molecular gas (Das, Boone & Viallefond 2010).

3 OBSERVATIONS AND DATA REDUCTION

3.1 HCT data

The LSB galaxies were observed using the 2-m Himalayan Chandra Telescope (HCT) at the Indian Astronomical Observatory (IAO), Hanle, which is remotely controlled from the Centre for Research and Education in Science and Technology (CREST), Indian Institute of Astrophysics (IIA), Bangalore. The spectra were obtained using a 11 arcmin × 1.92 arcsec slit (#167l) in combination with a grism #7 (blue region) and grism #8 (red region) which cover the wavelength ranges of 3700–7200 and 5500–9000 Å with dispersions of 1.46 and 1.26 Å pixel$^{-1}$, respectively. The spectral resolution is around 33.7 km s$^{-1}$.

Table 1. The sample of LSB galaxies.

| Galaxy       | Other name       | Galaxy type | Velocity$^a$ (km s$^{-1}$) | Distance$^b$ (Mpc) | Galaxy coordinates (J2000) | Galaxy inclination | Galaxy size (arcmin) | Absolute magnitude ($M_B$) |
|--------------|------------------|-------------|-----------------------------|--------------------|---------------------------|---------------------|------------------------|--------------------------|
| UGC 1378     | PGC 007247       | (R)SB(rs)a  | 2935                        | 43                 | 01$^h$56$^m$19$^s$.2 $+$ 73.1658$''$ | 68.6                | 3.4                    | -24.01                   |
| UGC 1922$^c$ | PGC 009373       | S           | 10 894                      | 151                | 02$^h$27$^m$45$^s$.8 $+$ 28.12$'$33$''$ | 29.6                | 2.1                    | -25.25                   |
| UGC 3968     | PGC 021636       | SB(r)c      | 6780                        | 94                 | 07$^h$42$^m$52$^s$.2 $+$ 66.15$'$30$''$ | 37.8                | 1.4                    | -23.55                   |
| UGC 4219     | PGC 022766       | SA(rs)b     | 12 433                      | 170                | 08$^h$06$^m$42$^s$.8 $+$ 39.05$'$25$''$ | 44.7                | 1.1                    | -24.37                   |
| UGC 6614     | PGC 036122       | (R)SA(r)    | 6532                        | 86                 | 11$^h$39$^m$14$^s$.9 $+$ 17.08$'$37$''$ | 29.9                | 1.7                    | -23.70                   |
| UGC 6754$^d$ | PGC 036740       | SA(rs)b     | 7025                        | 96                 | 11$^h$46$^m$47$^s$.2 $+$ 20.40$'$32$''$ | 29.1                | 3.0                    | -24.74                   |
| UGC 6968     | PGC 037704       | S           | 8232                        | 113                | 11$^h$58$^m$44$^s$.6 $+$ 28.17$'$22$''$ | 44.7                | 2.8                    | -24.04                   |
| UGC 7357     | PGC 039640       | SAB(s)c     | 6682                        | 91                 | 12$^h$19$^m$13$^s$.4 $+$ 22.25$'$54$''$ | 48$^c$               | 1.6                    | -22.17                   |
| F568–6       | Malin 2          | Sd/         | 13 830                      | 189                | 10$^h$39$^m$52$^s$.5 $+$ 20.50$'$49$''$ | 38$^c$               | 1.5                    | -25.50                   |

$^a$Heliocentric velocities from NED; $^b$Galactocentric distances from NED assuming $H_0 = 73$ km s$^{-1}$ Mpc$^{-1}$; $^c$ IC 226; $^d$ NGC 3883.

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Table 2. Observation details of long-slit spectra obtained from HCT.

| Galaxy   | Date of obs. | Exp. timea | Gr7 / Gr8 (s) |
|----------|--------------|------------|---------------|
| UGC 1378 | 2006-11-22   | 3600 / 3600|               |
| UGC 1922 | 2006-12-22   | 3600 / 3600|               |
| UGC 3968 | 2006-11-22   | 1800 / 3600|               |
| UGC 4219 | 2007-02-19   | 2400 / 2400|               |
| UGC 6614 | 2006-07-05   | 3600 / 3600|               |
| UGC 6754 | 2007-02-19   | 1800 / 2400|               |
| UGC 6968 | 2007-05-14   | 1800 / 2400|               |
| UGC 7357 | 2007-02-19   | 2400 / 1510|               |
| F568−6   | 2006-12-22   | 3600 / 3600|               |

aExposure times in the grism 7 (blue) and grism 8 (red).

≈8.7 Å [398 km s⁻¹ full width at half-maximum (FWHM) or σ = 169 km s⁻¹ at Hα] for grism #7 and ≈7 Å (σ = 136 and 103 km s⁻¹ at Hα and Ca II triplet, respectively) for grism #8. The slit was placed at the centre of the galaxy covering a central region of ≈2 × 5 arcsec² (1 arcsec corresponds to 415 pc at a redshift of ≈0.03).

Data reduction was carried out using the standard tasks available within IRAF⁴ which include bias subtraction, extraction of one dimensional spectra, wavelength calibration using the ferro argon lamp for grism #7 and ferrous neon lamp for grism #8. The wavelength-calibrated spectra were flux-calibrated using one of the spectroscopic standards of Oke (1990) observed on the same night, and then corrected for the redshifts of the galaxies. Flux-calibrated spectra were corrected for galactic extinction using Schlegel, Finkbeiner & Davis (1998). The spectra were not corrected for intrinsic dust extinction because LSB galaxies are known to have intrinsically less dust (Greene & Ho 2007; Mei, Yuan & Dong 2009). The blue and the red spectra were combined together with the help of scombine within spectral package using a suitable scale factor estimated at the flat continuum portions of the overlapping part of the spectra. A log of the observations is presented in Table 2 and the flux-calibrated HCT spectra are plotted in Fig. 1. We have used the HCT observations to identify the LSB galaxies that host AGN activity. The BH masses and bulge velocity dispersions were determined using Sloan Digital Sky Survey (SDSS) data for all but one of these galaxies.

3.2 SDSS DR7 data

Our pilot project on LSB galaxies was started in the year 2006 wherein careful selection of objects for which SDSS data were unavailable was considered. But when the Data Release 7 (DR7) data were released to the astronomy community, we found that a few galaxies from our sample were included. The resolution of the SDSS data is better (~70 km s⁻¹). Due to this, we have used SDSS DR7 data of our sample LSB galaxies for modelling/estimating the BH masses and velocity dispersions. For measuring the stellar velocity dispersion, SDSS offers a set of about 32 spectra of giant G and K stars of old open cluster M67. The stellar templates were observed in an identical manner as the SDSS LSB spectra and hence effects arising due to template mismatch are minimal. SDSS spectra are observed through a fibre of 3-arcsec diameter which transforms into an area of 2.9-kpc diameter for a redshift of z ~ 0.021. This area includes sufficient stellar light, nevertheless with stellar templates observed in the same setup, most of the stellar light would be removed after decomposition. In comparison, HCT spectra cover an area of ≈5.4 × 13.5 kpc² at the same redshift and the stellar templates were not observed in the same setup. Thus, for the estimation of BH masses after decomposing the broad and narrow components in the Hα region, and for the stellar velocity dispersion, we use SDSS spectra to give a conservative estimate of the above parameters.

4 SPECTRAL DECOMPOSITION

The emission lines appear weak in our sample, but the Hα emission line is clearly present in several of the galaxies. In order to isolate the Balmer and major nebular emission lines better, we have decomposed the observed spectrum into different constituents. Major contribution to the observed spectra arises from the underlying stellar population, and we use high-resolution model spectra of STARBURST99 (Leitherer et al. 1999) after degrading it to the resolution of the observed spectra. While a composite spectrum based on stellar spectral libraries would have been more realistic, STARBURST99 is simpler to use. The decomposition was executed only up to the wavelength of 7000 Å as the STARBURST99 high-resolution model spectra are available only up to the above mentioned wavelength.

The [N II] λ6584 and [O III] λ5007 lines along with Hα and Hβ lines are used to calculate oxygen abundance assuming the empirical relation obtained by Pettini & Pagel (2004). The oxygen abundances and hence metallicities are close to solar in value, particularly for F568−6 and UGC 6614 [see also McGaugh (1994) for UGC 6614]. The exception is the galaxy UGC 7357 which may have metallicity slightly less than solar. We have hence adopted solar abundances in applying the STARBURST99 model. The method of Mei et al. (2009) was used for decomposition of stellar light, along with emission from the Fe I and Fe II complexes, and in a few cases, a power-law component. We use Véron-Cetty, Véron & Gonçalves (2001) spectra of I Zw 1 to model the Fe I and Fe II complexes. Levenberg–Marquardt algorithm (Press et al. 1993) was used for the decomposition.

Fig. 2 shows the decomposed spectra plotted at the bottom of each plot. These spectra now show only the gas emission due to star formation and/or the active nucleus.

According to Schombert (1998), in their sample of LSB galaxies, 95 per cent showed nuclear emission. Our sample consists of bulge-dominated LSB galaxies and is a subset of the Schombert sample. Out of the nine galaxies observed, we find that only four galaxies show broad Hα profiles emission, along with strong emissions from [N II], [S II], [O III] and [O I], which hint the presence of an AGN. The line fluxes of various lines are presented in Table 3. We have adopted SDSS spectra for estimating the fluxes of broad and narrow components of Hα and hence in the calculation of BH masses, as well as stellar velocity dispersions. The SDSS spectra were taken through a fibre aperture of 3 arcsec in diameter (corresponding to 2.9 kpc at a redshift of 0.05). The broad and narrow components of Hα are separated using the fitprofs task of IRAF. Fig. 3 shows the fits to the Hα line profiles. The broad Hα line in AGN spectra are generally asymmetric. The above procedure of multiple Gaussian fit results in slightly larger errors due to this. The Hα fluxes for broad and narrow components, Hα luminosity and FWHM of the broad Hα lines are all listed in Table 3.
We have adopted the penalized-pixel fitting (pPxF) algorithm of Cappellari & Emsellem (2004) for recovering the stellar velocity dispersion. pPxF is Gauss–Hermite parametrization (Gerhard 1993; van der Marel & Franx 1993) that works in the pixel space. The reason is that in pixel space it is easy to mask gas emission lines or bad pixels from the fit and the continuum matching can be directly taken into account (Cappellari & Emsellem 2004). Also, the estimation of measurement errors are simplified. pPxF creates an...
Figure 2. (a) Plots show observed HCT spectra on the top, with best-fitting Gyr model showing the age of the underlying stellar population as a dashed line. Fe I and Fe II template spectra taken from Véron-Cetty et al. (2001) are plotted as dot–dashed line. Dotted lines seen in UGC 1378, UGC 3968 and UGC 4219 are power-law continuum following Mei et al. (2009). The bottom spectra drawn as thick solid lines show the subtracted spectrum. The x-axis represents the rest-frame wavelength. (b) UGC 6614 and UGC 6968 are best fitted using only the stellar spectra from STARBURST99, while the spectra of UGC 7357 and F568–6 require additional power-law continuum shown as dotted lines in these plots.
Table 3. Fluxes of emission lines in the units of 10^{-15} erg cm^{-2} s^{-1} obtained from HCT spectra.a

| Galaxy   | [O iii]  | Hα      | [O ii]   | [O i]   | Hαb     | [N ii]  | [S ii]   |
|----------|---------|---------|----------|---------|---------|---------|---------|
|          | 3727 Å  | 4861 Å  | 5007 Å   | 6300 Å  | 6563 Å  | 6548 Å  | 6584 Å  | 6717 Å  | 6731 Å  |
| UGC 1378 |         |         |          |         |         |         |         |         |         |
|          | 5.75 ± 0.54 | (9.41 ± 0.84) | (10.12 ± 1.19) |         |         |         |         |         |         |
| UGC 1922 | 4.35 ± 0.67 | 3.22 ± 0.73 |          | (15.58 ± 1.88) | (18.72 ± 3.08) | (11.67 ± 2.60) | (9.93 ± 2.95) |         |         |
|          | 2.08 ± 0.13 |         |          |         |         |         |         |         |         |
| UGC 4219 | 1.10 ± 0.25 |         |          |         |         |         |         |         |         |
|          | (10.52 ± 1.80) | (12.41 ± 0.94) | (13.93 ± 2.88) | (15.63 ± 0.98) | (16.78 ± 3.91) | (15.63 ± 0.98) | (18.55 ± 2.13) |         |         |
|          | (15.80 ± 2.58) | (12.25 ± 1.83) | (7.45 ± 3.57) |         |         |         |         |         |         |
| UGC 7357 | 2.03 ± 0.08 | 0.45 ± 0.08 |          | 4.60 ± 0.06 | 1.16 ± 0.09 | 2.57 ± 0.07 | 2.31 ± 0.16 | 1.83 ± 0.13 |         |
|          | (8.51 ± 0.25) | (3.95 ± 0.48) |         | (8.21 ± 0.16) | (10.37 ± 0.78) | (9.85 ± 0.36) | (10.25 ± 0.36) | (11.12 ± 0.79) |         |
| F568−6   | 1.66 ± 0.26 | 1.55 ± 0.31 | 0.49 ± 0.39 |         |         |         |         |         |         |
|          | (12.57 ± 2.23) | (10.17 ± 1.56) | (9.65 ± 2.33) |         |         |         |         |         |         |

aThe values quoted inside the brackets for each of the galaxies are FWHM of each of the lines whose fluxes are given above.

bHα fluxes for the objects which do not host AGN.

Empirically, early K giants consistently provide the closest match to both the Mg b and Ca ii triplet regions of many AGN samples. Here, we have tried to measure the stellar velocity dispersion by fitting the Ca ii triplet lines for these galaxies, UGC 6614, UGC 6968 and F568−6. According to Greene & Ho (2007), the optimal spectral region for measuring σ depends on the Eddington ratio, continuum level of the AGN and redshift of interest which suggests that for z < 0.05, Ca ii triplet is the region of choice for Eddington ratio <0.5 for the most reliable measurement of σ. The pPXF code was applied to only Ca ii triplet region to estimate σ. Fig. 4 displays the fits to the data; fitting error of ~10 per cent is estimated from the residuals.

5 AGN ACTIVITY AND BLACK HOLE MASSES

5.1 Emission line diagnostic diagram

It is interesting to investigate the positions occupied by these LSB galaxies in the Baldwin–Phillips–Terlevich (BPT) diagnostic diagram [first given by Baldwin, Phillips & Terlevich (1981) and improved further by Veilleux & Osterbrock (1987) – see Kewley et al. (2001, 2006) and references therein]. Fig. 5 shows the diagnostic diagrams plotted for [O iii]/Hβ versus [N ii]/Hα, [S ii]/Hα and [O i]/Hα, respectively. Also plotted in these diagrams are the demarcation lines between starbursts, Seyferts and LINERs obtained from Kewley et al. (2001, 2006) and Kauffmann et al. (2003). From the plots, four galaxies appear strong candidates for AGN, showing LINER-like activity. Of these, the galaxies F568−6 and UGC 6614 also show a high value of [O iii]/Hβ ~1.5 when compared to other galaxies in the sample and could be Seyfert-like. It may be noted that the [O iii]/Hβ ratio for low-mass AGNs selected from SDSS is 1.9 for one kind of sample (Greene & Ho 2007). The width of the broad Hα lines observed in these galaxies is below ~2000 km s^{-1}, indicating that they both belong to the class of narrow-line Seyfert 1 galaxies (NLS1s).
respect to the bulge scalelength. Jorgensen, Franx & Kjaergaard (1995) transform the values to the equivalent of an aperture of radius $r_e / 8$, where $r_e$ is the effective bulge radius. The effective bulge radius is about 4.2 arcsec for UGC 6968 as calculated by Gavazzi et al. (2000) using near-IR $H$-band image of the galaxy. Though McGaugh (1994) has attempted only to fit the disc, the bulge is visible in their surface brightness profile plots for the galaxies UGC 6614 and F568—6. de Blok, van der Hulst & Bothun (1995b) have also obtained the surface brightness profile for UGC 6614 but fit only the disc. The effective bulge radius $r_e$ for the galaxies UGC 1922, UGC 6614 and F568—6 are not available in the literature. On the other hand, as pointed out by Ferrarese & Merritt (2000), the applied corrections for the velocity dispersion $\sigma_*$ are very small, the maximum correction being <5 per cent. Greene & Ho (2005) and
Pizzella et al. (2004) find that radial dependence of $\sigma_*$ is flat with less than 7 per cent correction for early-type galaxies. Following these arguments, we have not applied any correction based on $r_e$ to $\sigma_*$, the spectra are extracted from a region of $2 \times 5$ arcsec$^2$.

5.3 The mass of central black hole ($M_{\text{BH}}$)

The BH masses are calculated using the equation given in Greene & Ho (2007), using H$\alpha$ luminosity and FWHM. The masses are $\sim 0.3 \times 10^6 M_\odot$ for the galaxies UGC 1922, UGC 6968 and F568–6, and lie on the lower mass tail of the low-mass BH sample of Greene & Ho (2007) which has a median mass of $1.3 \times 10^6 M_\odot$. UGC 6614 has a slightly higher BH mass of $3.8 \times 10^6 M_\odot$. The average $L_{H\alpha}/L_{568}$ ratio calculated for their sample is about 0.4 and suggests that their sources are radiating at high fraction of Eddington limit (Greene & Ho 2007). We find the values of 0.18, 0.023, 0.046 and 0.106 for UGC 1922, UGC 6614, UGC 6968 and F568–6, respectively. While these are lower compared to the median for the sample of Greene & Ho (2007), they are within their observed range.

We could identify clear signature for AGN in four out of nine objects in our sample which agrees with the high (50 per cent) occurrence of AGN found by Schombert (1998) in LBGs.

5.4 Interesting case of UGC 6614

The emission line spectra of UGC 6614 obtained after the decomposition of stellar light shows an interesting feature. A bump is noticed bluewards of the H$\alpha$ emission from the galaxy. This blue bump is noticeable in the observed flux-calibrated spectra before spectral decomposition but is clearly seen after the decomposition. The blue bump is the excess emission at H$\alpha$ which could be arising from ionized gas travelling at speeds $\sim 3600 \text{ km s}^{-1}$ towards us, centred at 3920 km s$^{-1}$. The blue bump is also noticed bluewards of H$\beta$ and the velocities with which the gas is streaming out towards us $\sim 3600 \text{ km s}^{-1}$ (median value of H$\alpha$ and H$\beta$) centred at 3360 km s$^{-1}$ from H$\beta$, similar to H$\alpha$. This emission at H$\alpha$ and H$\beta$ wavelengths overlap, indicating the feature to be real as shown in Fig. 6. Das et al. (2009a) detected a compact core and a one-sided radio jet in UGC 6614 from 610-MHz map. An extended feature is also indicated in a low-resolution Very Large Array map at 1420 MHz (Das et al. 2009a). The blueshifted ionized gas emission could indicate a jet or hotspot along the line of sight. Similar asymmetric blue bumps of the [O iii] lines were detected from a bunch of type 1/type 2 Seyferts from SDSS DR2 sample by Greene & Ho (2005). These wings indicate radial motions in the narrow-line region, associated with an outflow. The outflowing components are principally responsible.

Table 4. H$\alpha$ flux for narrow and broad components in $\text{erg cm}^{-2} \text{s}^{-1}$, luminosity of broad H$\alpha$ line, FWHM of the broad H$\alpha$ line, $\sigma_*$ calculated using Ca II triplet lines from SDSS spectra for three galaxies UGC 6614, UGC 6968 and F568–6. Due to unavailability of SDSS data for UGC 1922, HCT spectra are used for estimation of BH mass.

| Galaxy   | H$\alpha^a$ | $L_{H\alpha}$ | FWHM$^b$ | $\sigma_*$ | $M_{\text{BH}}$ |
|----------|-------------|---------------|----------|------------|----------------|
|          | Broad       | Narrow        | ($\times 10^6 \text{ erg s}^{-1}$) | ($\text{km s}^{-1}$) | ($\times 10^6 M_\odot$) |
| UGC 1922 | 8.13 ± 1.50 | 4.79 ± 1.93   | 2.21 ± 0.41 | 855.7 ± 140.7 | 0.39$^{+0.18}_{-0.15}$ |
| UGC 6614 | 32.77 ± 3.62 | 5.11 ± 0.71   | 2.91 ± 0.02 | 2456.5 ± 167.3 | 3.89$^{+1.23}_{-1.04}$ |
| UGC 6968 | 3.54 ± 1.68 | 1.83 ± 0.69   | 0.54 ± 0.01 | 1244.7 ± 742.8 | 0.45$^{+0.81}_{-0.38}$ |
| F568–6   | 2.01 ± 0.84 | 0.93 ± 0.40   | 0.85 ± 0.02 | 899.6 ± 372.4  | 0.29$^{+0.32}_{-0.20}$ |

$^a$H$\alpha$ fluxes of the broad and narrow components in units of $10^{-15} \text{ erg cm}^{-2} \text{s}^{-1}$.

$^b$FWHM of the broad line of H$\alpha$. 

Figure 5. Diagnostic diagrams for the sample of LSB galaxies, observed from HCT. The dotted line in the leftmost figure, log([O iii]/H$\beta$) versus log([N ii]/H$\alpha$), is the starburst–Seyfert demarcation taken from Kauffmann et al. (2003). The solid lines showing the demarcation in log([O iii]/H$\beta$) versus log([S ii]/H$\alpha$) and log([O iii]/H$\beta$) versus log([O i]/H$\alpha$) are taken from Kewley et al. (2001). The straight line drawn in the centre and right plots is the Seyfert–LINER demarcation line taken from Kewley et al. (2006). The [O i] emission was clearly detected only in four of the galaxies UGC 1922, UGC 6614, UGC 6968 and F568–6. These galaxies definitely host near-Seyfert kind of nuclei. UGC 7357 and UGC 4219 clearly fall in the starburst regime, and the galaxy UGC 3968 might be hosting a starburst–AGN composite nucleus as seen from the diagnostic diagrams.
for imparting supervirial motions to the gas and originate from a more compact region closer to the centre (Greene & Ho 2005).

5.5 The $M_\text{BH}$–$\sigma_\ast$ plot

The Ca II triplet linewidths and masses of BHs for the three galaxies in our sample are shown in the $M_\text{BH}$–$\sigma_\ast$ plot in Fig. 7. Also plotted in the figure are the linear regression lines given by Tremaine et al. (2002), Ferrarese & Ford (2005) and Gültekin et al. (2009) (dotted, dashed and solid lines, respectively) for $M_\text{BH}$ against $\sigma_\ast$. The low-mass AGNs hosted within LSB galaxies occupy the region just below the lowest mass BH of Circinus galaxy from the sample of Gültekin et al. (2009), well below the extrapolations of high-mass BHs. On the other hand, three AGNs in LSBs observed by Mei et al. (2009) in the BH mass range of $2.8-20 \times 10^5 M_\odot$ lie closer to the Tremaine et al. (2002) relation, though systematically lower. It would be of interest to study more LSB galaxies and low-luminosity AGN of Greene & Ho (2007) for a better understanding of faint luminosity end of $M_\text{BH}$–$\sigma_\ast$ relation.

6 DISCUSSION

6.1 Intermediate-mass BH (IMBH) in GLSB galaxies

One of the main results of our spectroscopic study is the detection of broad Hα emission in GLSBs and the subsequent estimation of nuclear BH masses from SDSS spectra in bulge-dominated GLSB galaxies. The AGNs fall in Seyfert–LINER region in the diagnostic diagram (Fig. 5).

We obtained masses $\sim 3 \times 10^6 M_\odot$ for three GLSB galaxies in our sample, which fall in the IMBH range rather than the SMBH range. A higher BH mass is estimated for UGC 6614 which is $\sim 3.8 \times 10^6 M_\odot$ and a similar estimate was given earlier by Das et al. (2009b) based on a low-resolution optical spectrum from Sprayberry et al. (1995). Another estimate of $\sim 1.2 \times 10^5 M_\odot$ was derived later from AGN X-ray variability studies by Naik et al. (2010), which is lower than the present estimate. It must be borne in mind that these estimates are fairly approximate as they are based on the assumption that the gas in the broad-line region in the AGN is in virial equilibrium (Kaspi et al. 2000).

IMBHs are fairly rare in the galactic nuclei and have been detected mainly in late-type spirals (Filippenko & Ho 2003; Greene & Ho 2004; Satyapal et al. 2007), nearby galaxies (Seth et al. 2010) or dwarf galaxies (Barth et al. 2010). They are difficult to detect dynamically at large distances; hence AGN activity is one of the main methods through which we detect them. The presence of IMBHs in GLSB galaxies is surprising as their bulges are well developed; in fact, a SMBH would be far more typical for these bulges. This suggests that the lack of disc evolution in these extreme late-type galaxies has affected the evolution of their nuclear BHs. Galactic disc activity contributes to the growth of SMBHs through gas inflow, star formation and mass accumulation in the nuclei of spiral galaxies as observed in bulge-dominated, star-forming early-type spirals. Large-scale disc instabilities such as bars and spiral arms exert gravitational torques that funnel gas into galaxy centres leading to nuclear star formation and the build-up of central mass concentrations (e.g. Friedli & Benz 1993). This can result in the growth of nuclear BHs and bulges in galaxies (Kormendy & Kennicutt 2004). This process of disc evolution leading to the growth of central mass concentrations in galaxies is prevented from happening or slowed down when there is a dominant dark matter halo (Ostriker & Peebles 1973). Thus, the lack of disc evolution and relatively low mass of the BH may share the same origin – which is the presence of a dominant dark halo in the galaxy.
6.2 Constraining the $M$–$\sigma$ relation for extreme late-type galaxies

In the past 10 years, the $M$–$\sigma$ and $M$–$L$ relations have become established benchmarks for galaxy and BH evolution theories. Our present work affects these correlations in two ways: first, it helps constrain the low-mass end of the $M$–$\sigma$ correlation, and secondly, it helps constrain the scatter in the plot (Gültekin et al. 2010). Graham (2008a,b) found that the scatter is actually due to systematic offsets for different types of galaxies while Hu (2008) found such offsets between galaxies with pseudo-bulge in contrast to classical bulge. The low-mass end of the $M$–$\sigma$ relation is populated by late-type (Goulding et al. 2010). Also, studies of nearby observations of three line (Fig. 7). It also suggests that dwarf galaxies and extreme late-type galaxies have different evolutionary paths compared to early-type galaxies and the more massive ellipticals at the high SMBH end of the $M$–$\sigma$ relation. Models of galaxy evolution thus need to incorporate late-type systems such as GLSB galaxies in their overall picture.

The late-type spirals also increase the scatter in the correlation which is tighter when only ellipticals and early-type spirals are included (Tremaine et al. 2002; Beifiori et al. 2009). Many theoretical studies have been undertaken to explain the $M$–$\sigma$ correlation and predict the high-mass end of the plot (Natarajan & Treister 2009). Dalla Bontà et al. (2009) carried out $HST$ observations of three brightest cluster galaxies (BCGs) and estimated masses of SMBHs to be $\sim 10^8 M_\odot$ present in these BCGs. While for one galaxy, SMBH mass correlates well in the $M$–$\sigma$ and $M$–$L$ plot at the high-mass end, the other two galaxies show inconsistencies with the two relations. The sample is small to derive any conclusions, but hints that there could be scatter in the SMBH scaling relations at the high-mass end as well (Dalla Bontà et al. 2009). One may also note here that Batcheldor (2010) suggests that the SMBH $M$–$\sigma$ relation is actually an upper limit.

However, the low-mass end does not appear to have a clear cut-off according to most models (Volonteri & Natarajan 2009). In fact, we could be missing observationally a large fraction of the lower mass BHs in the centres of galaxies. Thus, there is an increase in the scatter at the low-mass end of the correlation. This scatter could be due to measurement errors or could be intrinsic to the BH evolution processes in the galaxies themselves (Volonteri 2007). A few of the NLS1 galaxies observed (Grupe & Mathur 2004; Mathur & Grupe 2005) lie below the $M$–$\sigma$ line for normal galaxies similar to our LSBs.

One of the processes for BH evolution could be BH growth by accretion in well-formed bulges, probably after a major merger, which increases the mass of BH, naturally moving closer to the $M$–$\sigma$ for normal galaxies (Grupe & Mathur 2004). Our present study is thus important for understanding the overall trends in the low-mass end of the BH mass spectrum.

6.3 AGN evolution in late-type galaxies

Studies have shown that the space density of high-luminosity AGNs peaks at redshift of $z \sim 2$; this is also the redshift at which the most massive SMBHs were formed in galaxies (Cowie et al. 2003; Hasinger, Miyaji & Schmidt 2005). However, in the local universe, the most rapidly growing BHs appear to be those in the lower mass range of $10^7$–$10^8 M_\odot$ (Goulding et al. 2010). Also, studies of nearby galaxies show that it is the most massive BHs in late-type galaxies that are growing at the present epoch (Schawinski et al. 2010). The GLSB galaxies in our sample fall into the latter category as they have large bulges; though they have lower BH masses, they appear to be accreting and hence luminous in the optical domain.

6.4 Decoupled bulge–disc evolution in GLSB galaxies

As suggested by Das et al. (2009b), the bulges of GLSB galaxies appear to be very evolved compared to their discs. In general, bulges form in two ways: one is through repeated galaxy mergers or accretion events that lead to the formation of a central spheroidal mass distribution (Springel, Di Matteo & Hernquist 2005). The second is through secular evolutionary processes where disc instabilities lead to bars, spiral arms, gas infall and the evolution of a discy pseudo-bulge (Kormendy & Kennicutt 2004). These processes result in disc star formation and enhanced disc structure, both of which are not observed in most GLSB galaxies; instead their discs are metal-poor and often fairly featureless. Therefore, the bulges in GLSB galaxies probably formed in a different way; one possibility is that galaxy mergers resulted in spheroidal bulges and then the discs were rebuilt from accreted gas (Springel & Hernquist 2005). Such an evolutionary scenario would lead to a bulge that is relatively decoupled from its disc or its central BH.

6.5 BHs in halo-dominated galaxies

Although the correlation of BH mass and galaxy properties is now well established, it is still not clear exactly what regulates BH growth (see e.g. Booth & Schaye 2010, and references therein). Mass accretion close to the BH, bulge mass and the mass of the dark matter halo are some of the factors important for regulating BH growth in galaxies. It is not clear which factor is the most important or whether all the processes play a role. Several theoretical studies have explored how the potential of the dark halo may regulate bulge evolution and BH growth (Silk & Rees 1998; Xu, Wu & Zhao 2007; Booth & Schaye 2010) and there are observational studies that indicate a correlation between the dark halo and BH mass (Ferrarese 2002; Baes et al. 2003; Pizzella et al. 2005). On the other hand, some studies show that nuclear BH masses do not correlate with the dark matter haloes of galaxies and dark matter gravity is not directly responsible for BH growth (Ho 2007; Kormendy & Bender 2011). Such studies suggest that SMBHs co-evolve with classical bulges or ellipticals only. GLSB galaxies are halo-dominated and often bulge-dominated as well. Hence, they are ideal systems to study the dark halo–BH relation and this should be investigated in future studies.

7 CONCLUSION

(i) The paper presents spectroscopic observations of the nuclear regions of nine LSB galaxies observed in the wavelength range 3700–9000 Å. The stellar light has been subtracted from the nuclear spectra to obtain only gas emission spectra. Broad Hα lines along with strong [Nii], [Sii] and [Oii] lines are detected in four galaxies namely UGC 1922, UGC 6614, UGC 6968 and F568–6, confirming the presence of AGN activity in these LSB galaxies. SDSS spectra of three galaxies namely UGC 6614, UGC 6968 and F568–6 are used to estimate the BH masses and stellar velocity dispersion as the resolution of the SDSS spectra is good enough ($\sim 70 \text{ km s}^{-1}$) to give a conservative estimate on the above parameters.

(ii) The BPT AGN diagnostic diagram was created using the emission line ratios. It is clearly seen that the above four galaxies
lie in the AGN regime and more closely in the Seyfert regime. UGC 3968 might also host a starburst–AGN composite nucleus.

(iii) The broad Hz linewidths (900–2500 km s$^{-1}$) and luminosities (10$^{49}$ erg s$^{-1}$) are used to deduce the nuclear BH masses in the aforementioned galaxies; the masses for three galaxies are $\sim 3 \times 10^6 M_\odot$ and for UGC 6614 the BH mass is estimated to be about 3.8 $\times 10^6 M_\odot$. The masses suggest that the nuclei of LSB galaxies have IMBHs rather than the SMBHs found in the centres of brighter galaxies. UGC 6614 also shows an interesting feature of a blueshifted bump of H$\alpha$ emission which can be attributed to outflow of gas travelling at speeds of 3600 km s$^{-1}$ towards us. The blue bump feature is detected in the H$\alpha$ region as well. There could be more such AGN in the sample that may be identified through other means such as the reverberation technique with improved sensitivity.

(iv) The stellar velocity dispersion, $\sigma_*$ is measured for the three galaxies, UGC 6614, UGC 6968 and F568–6; the values lie between 150 and 210 km s$^{-1}$. The three low-mass BHs lie below the standard line in the $M_\ast-\sigma_*$ plot and lower than the ones studied by Mei et al. (2009).

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