An X-ray bright nucleus in the low-surface-brightness galaxy UGC 6614

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ABSTRACT

We report a study of the X-ray emission from the nuclear region of the low-surface-brightness (LSB) galaxy UGC 6614. Very little is known about the central objects in LSB galaxies, especially their X-ray properties and X-ray spectra. In this study we have used XMM–Newton archival data to study the characteristics of the X-ray spectrum and the X-ray flux variability of the active galactic nucleus (AGN) in the LSB galaxy UGC 6614. The nucleus of UGC 6614 is very bright in X-ray emission with an absorption-corrected 0.2–10.0 keV luminosity of \(\sim 1.1 \times 10^{42}\) erg s\(^{-1}\). The X-ray spectrum is found to be power-law type with a moderate column density. A short time-scale of intensity variation and large X-ray flux are indicative of the presence of a black hole at the centre of this galaxy. Using the method of excess variance, we have determined the black hole mass to be \(\sim 0.12 \times 10^9\) M\(_\odot\). The X-ray spectral properties are similar to that of the Seyfert I-type AGNs. Our study thus demonstrates that although LSB galaxies are poor in star formation, they may harbour AGNs with X-ray properties comparable to that seen in more luminous spiral galaxies.

Key words: galaxies: active – galaxies: evolution – galaxies: individual – galaxies: nuclei – galaxies: spiral – X-rays: galaxies.

1 INTRODUCTION

Most of the X-ray bright active galactic nucleus (AGN) in our nearby universe (\(z < 1\)) are either bulge-dominated early-type galaxies or disk galaxies that have recently undergone minor mergers or bar instabilities (Georgakakis et al. 2009; Gabor et al. 2009; Pierce et al. 2007). The latter processes are accompanied by vigorous star formation and gas infall towards the nucleus. Hence the host galaxies are optically bright and their nuclei often show strong AGN activity (Ho, Filippenko & Sargent 2003). Late-type spiral galaxies are, however, not as bright as early-type galaxies. They are generally poor in star formation and if AGN activity is present, it is usually weak (Ho 2008). The nuclear activity of such late-type systems is not as well studied or understood as those found in bright galaxies.

In this paper we present a study of the X-ray spectrum of an extreme-type of late-type spiral galaxy, a low surface brightness (LSB) galaxy. These galaxies are poorly evolved, halo-dominated systems and have diffuse, optically dim disks (Impey & Bothun 1997). AGN have been detected in their nuclei at optical wavelengths (Sprayberry et al. 1995; Impey, Burleigh & Sprayberry 2001), at radio frequencies (Das et al. 2006, 2007) and in X-ray emission (Das et al. 2009a). AGNs in LSB galaxies are usually associated with bulge-dominated LSB galaxies (Schombert 1998).

The X-ray properties of LSB galaxies are relatively unexplored. A recent Chandra study of eight giant LSB galaxies detected X-ray emission from the AGNs in two galaxies (Das et al. 2009a) as well as diffuse emission associated with the bulge in four of the eight sources. To date only two LSB galaxies have been observed by XMM–Newton, UGC 6614 and F568-6 (Malin 2). Of the two, UGC 6614 has an X-ray bright core. In F568-6, only a very faint X-ray source was detected in the XMM–Newton image; the faintness is probably due to the larger distance of the galaxy (\(D_{\text{Mpc}} \sim 200\)) compared to that of UGC 6614 (\(D_{\text{Mpc}} \sim 93\), where \(D_{\text{Mpc}}\) is the luminosity distance of the galaxy).

This paper presents the first study of the nuclear X-ray spectrum of an LSB galaxy. X-ray imaging studies of LSB galaxies have been done earlier (Das et al. 2009a), but X-ray spectroscopic studies have not been done before. Using XMM–Newton archival data, we present a study of the nuclear X-ray spectrum of UGC 6614, which is a prototypical giant LSB galaxy. The galaxy is close to face on and has a prominent bulge surrounded by a ring-like feature (Rahman et al. 2007; Hinz et al. 2007). Its optical spectrum shows a broad H\(\alpha\) line typical of a Seyfert 1 nucleus (Schombert 1998). It has a bright nucleus at millimeter and centimeter radio wavelengths (Das et al. 2006, 2009b). The optical R band image of the galaxy with the contours of X-ray emission overlaid is shown in Fig. 1 and the

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The figure shows the optical R band image of the galaxy with the contours of X-ray emission overlaid.

Table 1. Parameters of UGC 6614.

| Parameter                          | Value                                      |
|------------------------------------|--------------------------------------------|
| Galaxy type (R)Sa (NED)            |                                            |
| Galaxy position (RA, DEC)          | 11:39:14.9, +17:08:37 (2MASS)              |
| Velocity, redshift                 | 6352 km s^{-1}, 0.0212 (NED)              |
| Distance                           | 93.3 Mpc (NED)                             |
| Linear distance scale              | 0.45 kpc/arcsec                            |
| Disk inclination                   | 29.9° (Hyperleda)                          |
| Disk optical size (D_{25})         | 99.6 arcsec (RC3)                          |

Figure 1. The figure shows the optical R band image of the galaxy with the contours of X-ray emission overlaid.

2 DATA ANALYSIS AND RESULTS

UGC 6614 was observed with the XMM–Newton on 13 June 2002 for an exposure of ~13.4 ks. The raw events were processed using the Science Analysis System (SAS) package v7.0.0. Light curves in the energy range greater than 10 keV were extracted from PN and MOS event data (pattern zero only) to identify intervals of flaring particle background. A flare-type feature was seen in the hard X-ray light curves (>10 keV) of PN and MOS event data, which was subsequently excluded from further analysis. Light curves at different energy bands (0.2–2.0, 2.0–4.0, 4.0–10.0 and 0.2–10.0 keV) were extracted from PN and MOS event data by using the sas task xmmselect and selecting circular regions of radii 30 and 60 arcsec centred at the source position respectively. The energy spectra were extracted by selecting the corresponding circular regions around the source. The background light curves and spectra were extracted from the nearby source-free regions by selecting multiple circular regions of radii in 30–60 arcsec. The corresponding EPIC responses and effective area files were generated by using the sas tasks rmfgen and arfgen, respectively.

2.1 Timing analysis

Light curves at different energy bands, extracted from MOS-1, MOS-2 and PN event data as described above, were first combined to increase the signal-to-noise ratio. To investigate whether the source exhibits significant variations or not, we used light curves in 0.2–2.0, 2.0–4.0 and 4.0–10.0 keV energy ranges with a bin size of 500 s, and fitted with a constant. Given the count rate of the source, the number of photons in each bin was always sufficiently high for the use of the χ² test to investigate whether the source flux remained constant or not. In all the cases, the value of the reduced χ² was found to be greater than 15, thus rejecting the constant hypothesis with a high significance. This implies that the observed variations are intrinsic to the source. However, it should be remarked that at smaller time-scales, due to poor statistics, it is not possible to establish the presence or absence of variability using the χ² test.

In order to check the presence or absence of any flux-related spectral variations in UGC 6614, we plotted the ratio between the source count rates in 0.2–2 and 2–10 keV ranges as a function of 0.2–10 keV count rate. The resultant plot is shown in Fig. 3. The light curves from all three detectors were added together in corresponding energy ranges to improve the signal-to-noise level. From the figure, however, it is difficult to draw any conclusion on the spectral steepening with increasing flux, as seen in the case of Seyfert galaxies.

2.2 Excess variance and black hole mass estimation

The black hole mass (M_{BH}) is a key parameter in the study of AGNs. It can be determined by several methods of which one of the most reliable is the reverberation mapping technique (Peterson et al. 2004). It can also be determined from the X-ray variability of AGN

Figure 2. The figure shows the 0.2–10 keV light curves of UGC 6614 using data obtained from MOS-1 and MOS-2 (upper panel), PN (middle panel) and MOS-1, MOS-2 and PN detectors (bottom panel). The light curves are plotted for 500 s bin time. The missing data points in ~7–8 ks interval are due to the presence of a flaring event-like feature in the ≥10 keV light curve obtained only from the single events.
emission using the break in the power spectrum (Papadakis et al. 2004; McHardy et al. 2005) or the excess variance (Nikolajuk et al. 2004). In this section we use the method of excess variance to determine the mass of the black hole. This method is useful to estimate $M_{\text{BH}}$ in AGNs with short data coverage.

Excess variance is defined as the amplitude of variability in the light curve in excess of that expected from statistical fluctuations in the background level. This excess of the mean-squared normalized light curve is defined as (Nandra et al. 1997; Turner et al. 1999)

$$\sigma^2 = \frac{1}{N\mu^2} \sum_{i=1}^{N} [(X_i - \mu)^2 - \sigma^2_{\text{mean}}],$$

where $X_i$ is the count rate of $N$ points in the light curve with an unweighted arithmetic mean of $\mu$ and $\sigma^2_{\text{mean}}$ is the mean square error in the data set. The square root of the normalised excess variance ($F_{\text{amp}}$), indicates the root mean square variability amplitude.

The excess variance of the light curve between frequencies $v_1$ and $v_2$ can be calculated from the integral of the power density spectra. It is given by (Nikolajuk et al. 2004):

$$\sigma^2 = \int_{v_1}^{v_2} P(v)dv.$$

The determination of $M_{\text{BH}}$ is based on the assumption that the high-frequency break in the power spectrum ($v_{\text{bf}}$) is inversely related to $M_{\text{BH}}$, and the value of the product of power [$P(v)$] and frequency ($v$) at the high-frequency break is constant for all the sources and is independent of their mass. Therefore, as mentioned in Nikolajuk et al. (2004),

$$v_{\text{bf}} = C_1/M_{\text{BH}},$$

$$P(v_{\text{bf}})v_{\text{bf}} = C_2,$$

where $C_1$ and $C_2$ are constants. Thus, the mass of the black hole can be estimated if the excess variance of variability is known in a given frequency band, above the break frequency. If $T$ is the duration of the light curve and $\Delta t$ is the binsize of the light curve, then the mass of the black hole is given by

$$M_{\text{BH}} = C T - 2 \Delta t \sigma^2,$$

where $C$ is a constant that is determined by applying this method to a standard source. Using Cyg X-1 as a reference object of mass $20 M_{\odot}$ (Ziolkowski 2005; Nikolajuk et al. 2006) and Nikolajuk et al. (2006) determined the value of $C$ to be $1.92 \pm 0.5 M_{\odot}$ s$^{-1}$. Nikolajuk et al. (2006), though, used light curves in 2–10 keV band for their calculations, the use of light curves in different energy bands in the present case does not affect the final result as $\sigma^2$ is found to be similar at all energy bands.

Using the above method of excess variance, we have determined the normalized excess variance in light curves binned with 500 s, in different energy bands. Table 2 gives the estimated values of the excess variance ($\sigma^2$), the variability amplitude ($F_{\text{amp}}$) and the $M_{\text{BH}}$ in each case. The numbers in parentheses are the errors calculated using the $F_{\text{amp}}$ statistics described in Vaughan et al. (2003).

### Table 2. X-ray variability parameters for UGC 6614.

| Energy (keV) | $\sigma^2$ | $F_{\text{amp}}$ | $M_{\text{BH}} \times 10^8 M_{\odot}$ |
|-------------|------------|-----------------|--------------------------------------|
| 0.2–2.0     | 0.154(0.011) | 0.392(0.014) | 0.11(3) |
| 2.0–4.0     | 0.137(0.025) | 0.369(0.034) | 0.13(6) |
| 4.0–10.0    | 0.142(0.034) | 0.376(0.046) | 0.12(6) |

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### 2.3 Spectral analysis

Source and background spectra, response files and the effective area files for each of the three detectors were generated as described above. The source spectra were binned to a minimum of 20 counts per bin to improve the statistics and ensure the validity of the $\chi^2$ test. The spectral fitting was performed with the XSPEC package (v11). After appropriate background subtraction, simultaneous spectral fitting was done using the MOS1, MOS2 and PN spectra. All the spectral parameters other than the relative normalization, were tied together for all three detectors. We fitted the 0.1–10.0 keV spectra with a power-law continuum component modified with interstellar absorption. The model was found to be statistically acceptable with a reduced $\chi^2$ of 1.1 for 225 degrees of freedom. The value of the $N_H$ was found to be $\sim 2 \times 10^{20}$ cm$^{-2}$, which is similar to that of the galactic value in the source direction. Therefore, we fixed the value of $N_H$ at the galactic value ($1.93 \times 10^{20}$ cm$^{-2}$) and estimated the best-fitting parameters. The energy spectrum of the source along with the residuals to the best-fitting model is shown in Fig. 4. The spectral parameters of the best-fitting model obtained from the simultaneous spectral fitting are given in Table 3.

### 3 DISCUSSION

The main result of this paper is that although UGC 6614 is a LSB galaxy, it hosts an AGN whose X-ray characteristics are similar to those found in more evolved, star-forming galaxies and Seyfert galaxies. In the following paragraphs we discuss the implications of our results.

(i) **An X-ray bright AGN in a LSB galaxy**

The nucleus of UGC 6614 has an X-ray luminosity of $L_X \sim 1.1 \times 10^{39}$ erg s$^{-1}$. This is similar to the X-ray emission observed from another giant LSB galaxy, UGC 2936 ($L_X \sim 1.8 \times 10^{39}$ erg s$^{-1}$; Das et al. 2009a). The flux is also comparable to the nuclear X-ray flux of nearby disk galaxies (Georgakakis et al. 2009). Further, like most of the Seyfert galaxies, UGC 6614 shows significant X-ray variability on short time-scales (Turner et al. 1999). This strongly indicates the presence of an active nucleus in UGC 6614. As mentioned
earlier in Section 1, the nucleus of UGC 6614 is also bright at radio and optical frequencies. The radio spectrum is flat between 1.4 and 110 GHz and the emission is compact in morphology (Das et al. 2006) and only at lower radio frequencies (610 MHz) does it appear extended as radio lobes or jets (Das et al. 2009b). Thus, although UGC 6614 is a low-luminosity galaxy whose evolution is slowed down by the presence of a dominant dark halo, its AGN characteristics are similar to more evolved, star-forming galaxies.

(ii) X-ray variability and BH mass

The X-ray emission shows variability at short time-scales. Intraday X-ray variability has been observed in most quasars and AGNs (e.g. Markowitz & Edelson 2001; Uttley, McHardy & Papadakis 2002), while some AGNs also show variability down to time-scale of minutes (e.g. MCG-6-30-15: Miniutti et al. 2007). The short-variability time-scale has strong implications; it restricts the size of the emission region and is also related to the efficiency of the central engine. The large amplitude, short time-scale X-ray variability of UGC 6614 indicates an accreting black hole as the source of nuclear energy in this galaxy. If the X-ray variability mechanism in UGC 6614 and nearby Seyfert galaxies are the same, then, using the method of Nikolajuk et al. (2004), we estimated that the mass of the central black hole in UGC 6614 is \( M_{\text{BH}} \sim 0.12 \times 10^6 \, M_\odot \). This is similar to the black hole mass determined in several low-luminosity Seyfert-like active galaxies, such as, the late-type spiral galaxy NGC 4395 (Vaughan et al. 2005), the dwarf elliptical POX 52 (Barth et al. 2004) and the dwarf Seyfert 1 SDSS J160531.84+174826.1 (Dong et al. 2007). However, an approximate estimate of \( M_{\text{BH}} \) from the H\alpha line luminosity and linewidth relation (Greene & Ho 2007) gives a value of \( M_{\text{BH}} = 1.06 \times 10^7 \, M_\odot \) (Das et al. 2009a), which is much higher than that derived from the X-ray variability. Both methods are approximate and have large dispersions in the black hole mass. But the H\alpha observations are very poor in resolution (Sprayberry et al. 1995) and can be considerably improved. In fact the larger \( M_{\text{BH}} \) value is only an upper limit for the mass. This is supported by recent H\alpha spectroscopic observations of the nucleus of this galaxy (Ramya et al. 2010, in preparation). The Eddington luminosity corresponding to \( M_{\text{BH}} \sim 0.12 \times 10^6 \, M_\odot \) is \( L_{\text{Edd}} = 1.7 \times 10^{41} \, \text{erg s}^{-1} \). The X-ray luminosity is already 10 per cent of the Eddington limit for this black hole mass. Vasudevan & Fabian (2009) reported a range of 15–150 for the bolometric correction in AGNs depending on the Eddington ratio. Thus the mass of the black hole in UGC 6614 is quite likely to be more than the nominal value determined from excess variance. In absence of knowledge about the SED of this object, we cannot obtain a more definite estimate for the black hole mass.

(iii) Implications for galaxy evolution

Although the existence of AGN and black holes (BHs) in giant LSB galaxies has been known for some time, their properties are not well understood. Some studies suggest that their black hole mass and central velocity dispersion (\( M - \sigma \)) relation is different from ellipticals and high-surface-brightness galaxies (Pizzella et al. 2005). They also appear to lie off the radio-X-ray fundamental plane (Das et al. 2009). However, more detailed studies are required to understand the nuclear properties of these galaxies. As mentioned earlier, giant LSB galaxies have optically dim disks but prominent bulges which often host relatively bright AGN. This suggests that the bulge and AGN evolved independently of the halo-dominated disks. This decoupled disk-nuclear evolution is unlike what we see in nearby star-forming spirals where the bulge-AGN evolution is related to the secular evolution of the galaxy as a whole (Kormendy & Richstone 1995). This type of bulge-AGN evolution does not fit into our present picture of galaxy evolution. To understand it requires a deeper study of the AGN characteristics and star formation history of UGC 6614.

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