A variable ULX and possible IMBH candidate in M51a

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ABSTRACT

ULX-7, in the northern spiral arm of M51, demonstrates unusual behaviour for an ultraluminous X-ray source, with a hard X-ray spectrum but very high short-term variability. This suggests that it is not in a typical ultraluminous state. We analyse the source using archival data from XMM-Newton, Chandra and NuSTAR, and by examining optical and radio data from HST and VLA. Our X-ray spectral analysis shows that the source has a hard power-law spectral shape with a photon index $\Gamma \sim 1.5$, which persists despite the source’s X-ray luminosity varying by over an order of magnitude. The power spectrum of the source features a break at $\sim 7 \times 10^{-3}$ Hz, from a low-frequency spectral index of $\alpha_l = 0.1^{+0.2}_{-0.1}$ to a high-frequency spectral index of $\alpha_h = 0.7^{+0.1}_{-0.3}$, making it analogous to the low-frequency break found in the power spectra of low/hard state black holes (BHs). We can take a lower frequency limit for a corresponding high-frequency break to calculate a BH mass upper limit of $1.6 \times 10^3 M_\odot$. Using the X-ray/radio fundamental plane we calculate another upper limit to the BH mass of $3.5 \times 10^4 M_\odot$ for a BH in the low/hard state. The hard spectrum, high rms variability and mass limits are consistent with ULX-7 being an intermediate-mass BH; however we cannot exclude other interpretations of this source’s interesting behaviour, most notably a neutron star with an extreme accretion rate.

Key words: accretion, accretion discs – black hole physics – galaxies: individual: M51 – X-rays: binaries – X-rays: individual: M51 ULX-7

1 INTRODUCTION

Ultraluminous X-ray sources (ULXs) are point sources that are located away from the centre of their host galaxies and have an X-ray luminosity $L_X > 10^{39}$ erg s$^{-1}$, the Eddington luminosity of a typical stellar-mass black hole (BH) with $M_{BH} \sim 10 M_\odot$ (Özel et al. 2010; see Feng & Soria 2011 for a review of ULXs). Many of these sources can be explained as stellar-mass BHs accreting at or close to the Eddington limit (e.g. Middleton et al. 2013). However for sources with $L_X > 3 \times 10^{39}$ erg s$^{-1}$, this is often not sufficient. Given that their non-nuclear nature rules out the sources being active galactic nuclei (AGNs), and assuming that they are not background sources erroneously associated with the galaxy, they require one of two alternative explanations. Either they are BHs of unusually high mass – that is, intermediate-mass BHs (IMBHs) with $10^2 \lesssim M_{BH} \lesssim 10^5 M_\odot$ (Colbert & Mushotzky 1999) – or they exhibit an extreme accretion mechanism beyond the standard thin disc scenario, such as super-Eddington accretion (Poutanen et al. 2007) and/or geometrically beamed emission (King et al. 2001).

The origin of IMBHs requires exotic formation scenarios, such as the collapse of early-universe population III stars (Madau & Rees 2001). This, and the results of studies implying that all but the brightest sources of the ULX population make up the high luminosity tail of the high mass X-ray binary (HMXB) luminosity function in spiral galaxies and the low mass X-ray binary (LMXB) luminosity function in elliptical galaxies (Swartz et al. 2004, 2011; Walton et al. 2011; Mineo, Gilfanov & Sunyaev 2012), points to the majority of ULXs being super-Eddington accreting stellar-mass sources. This is strengthened by results from the spectral analysis of these sources, which exhibit a characteristic two-component spectrum with a soft excess and a high energy downturn at $\sim 3 – 5$ keV that is not found in sub-Eddington accretion states (e.g. Stobbart, Roberts
These tend to be objects too luminous to be explained by soft thermal emission (e.g. Feng & Kaaret 2005; Feng et al. 2005; Terashima et al. 2006) found significant long- and short-term variability, although they did not find a period, suggesting that the variability is instead due to aperiodic noise from stochastic processes. The source is near to a young massive star cluster with age \( \tau \sim 12 \) Myr (Abolmasov et al. 2007) and has previously been found to have a changing spectral shape by Yoshida et al. (2010), ranging from fairly flat (\( \Gamma < 1.5 \)) to soft (\( \Gamma \sim 2 - 3 \)), although any contribution from the host galaxy to the emission was not considered in their study.

While they often demonstrate spectral variability between observations (e.g. Kajava & Poutanen 2009), strong short term variability is not a common feature of ULXs (e.g. Feng & Kaaret 2005; Heil, Vaughan & Roberts 2009). In the broadened disc/hard ultraluminous/soft ultraluminous classification of ULX accretion regimes, high (>10%) fractional variability is predominantly seen in the soft ultraluminous state in which the X-ray spectrum is dominated by soft thermal emission (Sutton, Roberts & Middleton 2013). Furthermore, the variability is limited to the hard component of emission (Middleton et al. 2015a). A proposed mechanism for this is a clumpy wind that would be expected to be driven away from the disc by intense radiation pressure in super-Eddington accretion scenarios, and to intermittently obscure the hard central source in high-inclination systems, causing the spectrum to be dominated by soft thermal emission and variability to be imprinted on the hard emission component (e.g. Middleton et al. 2011, 2015a). However in the case of ULX-7, the spectrum is hard, which suggests that this source does not fit this model and may be in an accretion state more analogous to the low/hard state of stellar-mass BHs – in which case, this object might instead be a candidate IMBH, albeit emitting at a lower luminosity than other candidate IMBHs we are aware of to date.

Here we conduct our own analysis of ULX-7, examining its X-ray spectral and timing properties, as well as optical and radio data, to attempt to better characterise this fascinating source. In Section 2 we detail the reduction of archival data from XMM-Newton, Chandra, NuSTAR, the Hubble Space Telescope (HST) and the Very Large Array (VLA) telescopes. We present the results of our analysis in Section 3, and discuss the possibility of this source being a background AGN, a neutron star or an IMBH in Section 4, before presenting our conclusions in Section 5.

2 REDUCTION OF ARCHIVAL DATA

In this paper we will investigate this object from a multi-wavelength perspective, using archival data from a range of missions. We assume a source position of 13:30:01.0 +47:13:44 (J2000; Kilgard et al. 2005).

2.1 X-ray Observations

There were six observations of M51 by the XMM-Newton observatory over the course of eight years, between 2003 and 2011. The durations of observations with XMM-Newton are limited by visibility due to the position of M51 in the sky and the orbit of the telescope. The longest observation to date is \( \sim 52 \) ks. Data reduction was performed using v13.5.0 of the XMM-Newton Scientific Analysis System (SAS) and up-to-date calibration files. We used EPPROC and EMPROC to produce calibrated event lists for the pn and MOS detectors. The event lists were filtered for high-energy background flaring in accordance with the standard XMM-Newton SAS threads\(^2\), excluding intervals for which the \( > 10 \) keV count rate was \( \geq 35 \) ct s\(^{-1}\) in the EPIC-MOS data and the 10–12 keV count rate was \( \geq 4 \) ct s\(^{-1}\) in the EPIC-pn data.

XMM-Newton spectra and light curves were extracted using EVSELECT from 20 arcsecond radius regions around the source, filtering for patterns\( \leq 12 \) for the EPIC-MOS camera and patterns\( \leq 4 \) for the EPIC-pn camera. Background counts were extracted from an equally-sized region outside of the galaxy on the same chip, at a similar distance from the readout node. Redistribution matrices and auxiliary response files were generated using RMFGEN and ARFGEN respectively, and spectral data were grouped into bins of at least 25 counts, making sure not to oversample XMM-Newton’s intrinsic energy resolution by a factor more than three. Corrected lightcurves for EPIC-MOS and EPIC-pn were generated using EPICLCCorr with a bin size of 50 s and added together, using the same start and stop times as in Table 1.

\(^1\) The mean distance given by the NASA/IPAC Extragalactic Database (http://ned.ipac.caltech.edu/).

\(^2\) See the SAS User Manual at http://xmm.esac.esa.int/sas

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end times. All six observations have a quality warning flag due to the source being located within bright extended emission, which we characterise in Section 2.1.

While Chandra does not have the collecting area of XMM-Newton, it is not limited by visibility in the same way, and its orbit allows for far longer observations of M51. There have been eleven Chandra observations of M51 taken over the course of twelve years, between 2000 and 2012, the longest being ~190 ks (see Table 1) during a set of five deep observations in 2012. The Chandra data were reduced using V4.7 of the Chandra Interactive Analysis of Observations (CIAO) software package and reprocessed to produce up-to-date event lists.

Chandra spectra and light curves were extracted using the SPECEXTRACT and DMEXTRACT routines respectively from 3 arcsecond radius regions, with the same binning as the XMM-Newton data. Since ULX-7 is a point source, we set weight=no and correctpsf=yes. Background counts were collected from an annulus around the source between 3 and 20 arcseconds. This same annulus was also used to characterise diffuse emission surrounding the object in order to correct the XMM-Newton spectra – the background region in this case was taken from an equally-sized region outside of the galaxy. Between XMM-Newton and Chandra, we can examine the long-term variability of the source, as well as its short-term properties.

The advent of the NuSTAR mission allows us to probe spectral energies of > 10 keV for resolved sources. To date there is one observation of M51 using NuSTAR, performed in 2012, in which ULX-7 is detected along with the low-luminosity AGN and one other ULX in the galaxy. We reduced the NuSTAR data using the standard pipeline, NUPipeline, part of the NuSTAR Data Analysis Software (NuSTARDAS, v1.4.1; included in the HEASOFT distribution), with the instrumental calibration files from CALDB V20140414. The unfiltered event files were cleaned with the standard depth correction, significantly reducing the internal high-energy background, and passages through the South Atlantic Anomaly were removed. Source spectra and instrumental responses were produced for each of the two focal plane modules (FPMA/B) using NUPRODUCTS. Source spectra were extracted from a circular region of radius 25 arcseconds in order to avoid contamination from a potential nearby X-ray source, while background was estimated from a much larger region on the same detector as the source, avoiding all the other bright X-ray sources in M51. In order to maximise the good exposure, in addition to the standard (mode 1) data, we also reduce the available mode 6 data; see Walton et al. and Fuerst et al. (in preparation) for a description of NuSTAR mode 6. This provides an additional ~15% exposure, resulting in a total on-source time of 19 ks per FPM. Finally, owing to the low signal-to-noise, we combined the data from FPMA and FPMB using ADASCAPEC. The resulting NuSTAR spectrum provides a detection up to ~20–25 keV, and is rebinned to a minimum of 20 counts per bin for our spectral analysis.

A list of all X-ray observations is presented in Table 1. We calculate the flux between 0.3–10 keV (3.0–10 keV and 3.0–20 keV for the NuSTAR data) using the best-fitting absorbed power-law model if there are sufficient counts for a spectral fit. In the cases where there are a small number of data points we use WebPIMMS3 and the count rate to predict the flux, assuming a photon index of Γ = 1.5 (the average photon index of the best-fitting models to the data we were able to fit – see Section 3.1).

In the case of XMM-Newton observation X6, it should be noted that the flux is likely dominated by the surrounding diffuse emission rather than the source itself. The source flux varies between 3.0 × 10^{-14} erg cm^{-2} s^{-1} and 8.6 × 10^{-13} erg cm^{-2} s^{-1} in the 0.3–10 keV energy band over the course of all observations (i.e. its luminosity varies between 2.2 × 10^{38} erg s^{-1} and 5.1 × 10^{39} erg s^{-1}). This is an unusually high amount of flux variation for a ULX, even if we disregard fluxes calculated using WebPIMMS, in which case we still see variation of over an order of magnitude.

2.2 Radio Observations

In order to search for core radio emission from the ULX, we retrieved archival VLA A-array data at 1.5 GHz (project 11A142, August 2011). The data flagging and calibration was performed following standard procedures with the Common Astronomy Software Applications (CASA) software. The data were calibrated in amplitude using 3C286 as flux calibrator, while delay and phase solutions were derived from the phase calibrator J1327+4326 and interpolated and applied to the target source. The calibrated data were imaged in CASA using the CottonSchwab algorithm and natural weighting. The resulting beam has a size of 1.5 arcseconds × 1.4 arcseconds oriented at a position angle of 36.9 deg. No radio emission is detected at the Chandra position of the source within a positional error of 1 arcsecond. An upper limit on the 1.5 GHz radio flux density of 87 µJy beam^{-1} is derived from the local rms at the Chandra position. The 1.5 GHz radio image is shown in Fig. 1. Other studies of the radio emission in M51 have also not detected a counterpart to ULX-7 (Maddox et al. 2007; Rampadarath et al. 2015).

2.3 Optical Observations

M51 has been well observed by HST over the course of the mission’s lifetime, and was mapped in 2005 with the ACS/WFC camera as part of the Hubble Heritage project. We collected preprocessed data from the Hubble Legacy Archive, made up of exposures combined using the MULTI DRIZZLE routine. We used images in the F435W (B), F555W (V) and F814W (I) bands to locate possible optical counterparts to ULX-7. The 90% confidence circle

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3 https://heasarc.gsfc.nasa.gov/cgi-bin/Tools/w3pimms/w3pimms.pl
Table 1. Dates, durations and fluxes for X-ray observations of M51 with XMM-Newton, Chandra and NuSTAR.

<table>
<thead>
<tr>
<th>ID</th>
<th>Observation ID</th>
<th>Instrument</th>
<th>Observation Date</th>
<th>Exposure (ks)</th>
<th>Flux (×10^{-13} erg cm^{-2} s^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>X1</td>
<td>0112840201</td>
<td>MOS1</td>
<td>2003-01-15</td>
<td>20.66</td>
<td>1.9 ± 0.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MOS2</td>
<td></td>
<td>20.67</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>pn</td>
<td></td>
<td>19.05</td>
<td></td>
</tr>
<tr>
<td>X2</td>
<td>0212480801</td>
<td>MOS1</td>
<td>2005-07-01</td>
<td>35.04</td>
<td>7.6 ± 0.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MOS2</td>
<td></td>
<td>35.77</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>pn</td>
<td></td>
<td>24.94</td>
<td></td>
</tr>
<tr>
<td>X3</td>
<td>0303420101</td>
<td>MOS1</td>
<td>2006-05-20</td>
<td>39.60</td>
<td>5.9 ± 0.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MOS2</td>
<td></td>
<td>39.66</td>
<td></td>
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<td></td>
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<td>pn</td>
<td></td>
<td>30.90</td>
<td></td>
</tr>
<tr>
<td>X4</td>
<td>0303420201</td>
<td>MOS1</td>
<td>2006-05-24</td>
<td>29.77</td>
<td>8.5 ± 0.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MOS2</td>
<td></td>
<td>29.76</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>pn</td>
<td></td>
<td>23.18</td>
<td></td>
</tr>
<tr>
<td>X5</td>
<td>0677980701</td>
<td>MOS1</td>
<td>2011-06-07</td>
<td>9.80</td>
<td>5.2 ± 0.4</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MOS2</td>
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<td>9.51</td>
<td></td>
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<td>pn</td>
<td></td>
<td>5.13</td>
<td></td>
</tr>
<tr>
<td>X6</td>
<td>0677980801</td>
<td>MOS1</td>
<td>2011-06-11</td>
<td>1.60</td>
<td>1.1 ± 0.1d</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MOS2</td>
<td></td>
<td>1.60</td>
<td></td>
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<td></td>
<td></td>
<td>pn</td>
<td></td>
<td>2.30</td>
<td></td>
</tr>
</tbody>
</table>

\(^a\) Short ID used elsewhere within this paper for clarity.

\(^b\) Sum of the good time intervals after removal of background flaring events.

\(^c\) Deabsorbed flux in the energy range 0.3–10 keV for XMM-Newton and Chandra, and the ranges 3–10 keV and 3–20 keV for NuSTAR. The flux is determined from the best-fitting power-law model, excluding contribution from soft diffuse emission in the XMM-Newton observations (see Section 3.1). The NuSTAR fluxes are calculated from the best-fitting power-law model (with \(N_H = 1 \times 10^{21} \text{ cm}^{-2}\)) to the 3–10 keV data and the 3–20 keV data respectively.

\(^d\) Where there is insufficient data to calculate flux from a best-fitting model, we use WebPIMMS to find the deabsorbed flux, using the detected count rate and a power-law model with \(N_H = 1 \times 10^{21} \text{ cm}^{-2}\) and \(\Gamma = 1.5\).

for the Chandra ACIS-S instrument is 0.6 arcseconds, however it is also necessary to align the relative astrometry of the HST and Chandra images. We did this by selecting 2MASS objects within the M51 field and using the IRAF tools CCFIND, CCMAP and CCSETWCS to find the necessary corrections to the right ascension and declination. We found an offset of 0.1 arcseconds in the right ascension direction and 0.7 arcseconds in declination.

The source is located near to a young star cluster and has a number of possible optical counterparts. We performed photometry on these objects using the DAOPHOT II/ALLSTAR software package (Stetson 1987), a PSF-fitting routine (see Section 3.3), although due to the crowded nature of the field, we were only able to obtain limited constraints on the magnitudes in each band. Where the magnitude of an object was unconstrained, we used the various sources of detector noise to place a lower limit on the magnitude.

3 ANALYSIS & RESULTS

We analysed the archival data described in Section 2 in order to determine the properties of ULX-7. Optical and X-ray images of M51 from the HST, XMM-Newton, Chandra and NuSTAR telescopes, along with the location of ULX-7, are shown in Fig. 2. The source lies within diffuse X-ray emission in the northern spiral arm of its host galaxy.
Figure 2. Images of the M51 system, centred for convenience on 13:29:52.3 +47:12:45.3 (J2000). In all images, the position of the centre of M51a is marked with a cross, and ULX-7 is indicated by a 20 arcsecond radius white circle. Top left, HST true-colour image with the red, green and blue channels corresponding to the F814W, F555W and F435W bands respectively. Top right, XMM-Newton EPIC-pn image in the energy range 0.3–10 keV from observation X4. Bottom left, Chandra ACIS-S image in the energy range 0.3–10 keV from observation C8. Bottom right, NuSTAR image in the energy range 3–24 keV, smoothed with a 14 arcsecond Gaussian and with contours to aid visibility only.
Table 2. The temperature, flux and \( \chi^2 \) goodness of fit for the two mekal components used to fit the diffuse emission around ULX-7 in the deepest Chandra observations.

<table>
<thead>
<tr>
<th>ID (^a)</th>
<th>( kT_1 ) (keV)</th>
<th>( F_1 ) ((\times 10^{-14} \text{ erg cm}^{-2} \text{s}^{-1}))</th>
<th>( kT_2 ) (keV)</th>
<th>( F_2 ) ((\times 10^{-14} \text{ erg cm}^{-2} \text{s}^{-1}))</th>
<th>( \chi^2/\text{dof} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>C6</td>
<td>0.25(^\pm)0.08</td>
<td>1.3 \pm 0.3</td>
<td>0.6(^\pm)0.4</td>
<td>1.3 \pm 0.3</td>
<td>54.3/60</td>
</tr>
<tr>
<td>C7</td>
<td>0.22(^\pm)0.05</td>
<td>1.5 \pm 0.4</td>
<td>0.7(^\pm)0.3</td>
<td>1.0 \pm 0.2</td>
<td>84.2/73</td>
</tr>
<tr>
<td>C8</td>
<td>0.17(^\pm)0.10</td>
<td>1.0 \pm 0.3</td>
<td>0.4(^\pm)0.2</td>
<td>1.4 \pm 0.2</td>
<td>76.2/71</td>
</tr>
<tr>
<td>C9</td>
<td>&lt; 0.27</td>
<td>2.5 \pm 0.4</td>
<td>&lt; 1.0</td>
<td>0.5 \pm 0.2</td>
<td>14.1/21</td>
</tr>
<tr>
<td>C10</td>
<td>0.24(^\pm)0.05</td>
<td>2.0 \pm 0.4</td>
<td>0.8(^\pm)0.6</td>
<td>0.5 \pm 0.3</td>
<td>34.4/24</td>
</tr>
<tr>
<td>All (^b)</td>
<td>0.26(^\pm)0.03</td>
<td>1.9 \pm 0.1</td>
<td>0.8 \pm 0.2</td>
<td>0.6 \pm 0.1</td>
<td>279.9/258</td>
</tr>
</tbody>
</table>

\(^a\)The short observation ID as defined in Table 1. \(^b\)The best-fitting parameters when fitting all five observations simultaneously.

3.1 X-Ray Imaging & Spectral Analysis

The XMM-Newton image of the source and its environment (see Fig. 2) shows that it lies within extended diffuse emission. Therefore the XMM-Newton source spectra are likely to be contaminated by a soft thermal component. In order to characterise this component, we first examine archival data from the Chandra observatory, since its high spatial resolving power allows us to separate out the spectra of the source and of the surrounding gas.

To obtain sufficient counts from the Chandra data for analysis, we used only the five observations with exposure time > 50 ks. We extracted diffuse emission spectra from an annulus with an inner radius of 3 arcseconds around the source, and an outer radius of 20 arcseconds to be the same as the XMM-Newton footprint used for source analysis. There are no resolved point sources within the annulus. We took a background spectrum from a 20 arcsecond radius region centred to the north of the galaxy in an area with minimal diffuse emission.

All spectral fitting was performed with v12 of XSPEC (Arnaud 1996), and all Chandra and XMM-Newton observations are fitted in the 0.3–10 keV energy range with errors given at 90% confidence intervals. The data is binned (see Section 2.1) such that fitting can be performed using \( \chi^2 \) minimisation, and \( \chi^2 \) statistics used to determine the goodness-of-fit. The abundance tables of Wilms, Allen & McCray (2000) are used throughout.

The diffuse emission spectra were well-fitted using two mekal thermal plasma components: a cooler component at \( \sim 0.2 \) keV and a second warmer component at \( \sim 0.7 \) keV, consistent with previous studies into the diffuse emission of the galaxy (e.g. Owen & Warwick 2009). We also detected hard emission, requiring an additional hard component in the spectrum since attempting to fit the data without it causes one of the mekal components to take on an unrealistically high temperature. This hard component may be due to unresolved hard sources within the annulus, therefore we fitted it with an absorbed power-law (tbabs*powerlaw), allowing the photon index to vary. We set the hydrogen column density to \( N_\text{H} = 1 \times 10^{21} \text{ cm}^{-2} \) since preliminary fits to the ULX-7 source spectrum gave \( N_\text{H} \) of approximately this value and we would expect absorption by the surrounding interstellar medium (ISM) to be similar in the near vicinity. The power-law has \( \Gamma \sim 1–2 \) and would contribute < 0.1% of the total flux when combined with the source spectrum. For this reason, we expect that its effect on the spectrum of ULX-7 is negligible, so we do not include it in our characterisation of the diffuse emission itself.

\[ \text{The fit results for the diffuse emission are given in Table 2.} \]

Given that the temperature parameters are all consistent within the errors, and that we do not expect the diffuse emission to vary between observations if it originates in the ISM of M51, we performed a simultaneous fit of all five observations and used the best-fitting parameters (see Table 2) when fitting the XMM-Newton source spectra. An example of the diffuse emission spectrum is shown in Fig. 3.

While six XMM-Newton observations of ULX-7 exist, there is only sufficient data quality for spectral analysis from the first five. We fit the spectra of each of these first five observations with an absorbed power-law model and two additional mekal components to account for contamination from the diffuse emission (mekal+mekal+tbabs*powerlaw). We set the lower bound of \( N_\text{H} \) for the tbabs component to the Galactic foreground value\(^4\) of

\[ \text{foreground} \ N_\text{H} \text{ was obtained from the HEASARC} \ N_\text{H} \text{ calculator} \]

\[ \text{Fig. 3. The X-ray spectrum of the diffuse emission surrounding ULX-7 from observation C8, together with the best-fitting mekal+mekal+tbabs*powerlaw model, with mekal parameters as given in Table 2. The mekal components are plotted with dashed lines and the tbabs*powerlaw component with a dotted line. Events are grouped into 20 counts per bin.} \]
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\[ N_H = 1.8 \times 10^{20} \text{ cm}^{-2} \] and fixed the mekal parameters and normalisations to the average values determined from the Chandra results, which we take as a good first-order approximation to the contribution of diffuse emission to the spectrum. Most of the XMM-Newton source spectra are well-fitted by this model and exhibit fairly hard ($\Gamma \sim 1.5 - 1.6$) power-law emission. The exception is observation X3 for which we reject a simple absorbed power-law at $> 4\sigma$ significance. The fit for X3 undergoes moderate improvement ($\Delta \chi^2 \sim 17$ for 2 fewer degrees of freedom) by the addition of a multicolour disc component (mekal+mekal+tbabs*(diskBB+powerlaw)), although it is still rejected at $\sim 3.5\sigma$ significance. It is unclear from the residuals what a better model might be, so we are unable to find an acceptable fit for the data from this observation. It is possible that ULX-7 exhibits similar soft atomic features to those seen in other ULXs (e.g. Middleton et al. 2015b), however the presence of diffuse emission in the host galaxy complicates more detailed study of the soft end of the spectrum.

We also fit the Chandra source observations of sufficient data quality with an absorbed power-law model to ensure that they are consistent with the XMM-Newton results (we do not include the mekal components as we assume that the contribution from surrounding diffuse emission is negligible in the Chandra source data). As in the case of XMM-Newton, $N_H$ is given a lower limit of the Galactic foreground value and allowed to vary, except for observation C10 for which we set $N_H$ to $1 \times 10^{21}$ cm$^{-2}$ (the average value found from fits to other observations) since there is insufficient data to constrain it further. We find that the spectra are consistent with the same hard ($\Gamma \sim 1.5$) power-law shape as the XMM-Newton observations.

Best fit parameter values for XMM-Newton and Chandra are given in Table 3, and examples of high- and low-flux spectra and their power-law fits are shown in Fig. 4.

ULX-7 is strongly detected in the 8–24 keV band in the NuSTAR observation (Fig. 2), with a good signal found up to

![Figure 4. Example spectra of ULX-7 from XMM-Newton and Chandra at high and low fluxes, unfolded from the detector response and plotted between 0.3 and 10 keV, along with the best-fitting absorbed power-law model and the contribution from diffuse emission in the case of XMM-Newton. Fluxes can be found in Table 1, the diffuse emission parameters in Table 2, and best-fitting source parameters in Table 3. For the XMM-Newton spectra, pn data is plotted in black, MOS1 data in red and MOS2 in green. Top left, high-flux XMM-Newton observation X4. Top right, high-flux Chandra observation C7. Bottom left, low-flux XMM-Newton observation X1. Diffuse emission can be seen to be dominant at the soft end of this spectrum (< 1 keV). Bottom right, low-flux Chandra observation C10.](image-url)
The parameter values and goodness of fit for the XMM-Newton and Chandra source spectra when fitted with an absorbed power-law model (and a power-law with a multicolour accretion disc in the case of X3).

<table>
<thead>
<tr>
<th>ID</th>
<th>$N_H$ ($\times 10^{21}$ cm$^{-2}$)</th>
<th>$\Gamma$</th>
<th>$T_{in}$ (keV)</th>
<th>$\chi^2$/dof</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>XMM-Newton</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>X1</td>
<td>$0.6^{+0.6}_{-0.5}$</td>
<td>$1.7 \pm 0.2$</td>
<td>...</td>
<td>42.9/53</td>
</tr>
<tr>
<td>X2</td>
<td>$1.1 \pm 0.2$</td>
<td>$1.59 \pm 0.06$</td>
<td>...</td>
<td>231.2/177</td>
</tr>
<tr>
<td>X3</td>
<td>$1.0 \pm 0.2$</td>
<td>$1.57^{+0.07}_{-0.06}$</td>
<td>260.5/174</td>
<td></td>
</tr>
<tr>
<td>X4</td>
<td>$1.2 \pm 0.4$</td>
<td>$1.2 \pm 0.2$</td>
<td>$0.4 \pm 0.1$</td>
<td>243.7/172</td>
</tr>
<tr>
<td>X5</td>
<td>$0.6^{+0.6}_{-0.5}$</td>
<td>$1.45^{+0.06}_{-0.05}$</td>
<td>...</td>
<td>172.3/182</td>
</tr>
<tr>
<td><strong>Chandra</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C1</td>
<td>$1.5^{+0.9}_{-0.8}$</td>
<td>$1.3 \pm 0.2$</td>
<td>...</td>
<td>26.2/28</td>
</tr>
<tr>
<td>C3</td>
<td>$1.4 \pm 0.4$</td>
<td>$1.5 \pm 0.1$</td>
<td>...</td>
<td>67.2/94</td>
</tr>
<tr>
<td>C5</td>
<td>$0.4^{+0.4}_{-0.3}$</td>
<td>$1.3^{+0.5}_{-0.3}$</td>
<td>...</td>
<td>13.7/12</td>
</tr>
<tr>
<td>C6</td>
<td>$1.2 \pm 0.2$</td>
<td>$1.49 \pm 0.05$</td>
<td>...</td>
<td>244.1/215</td>
</tr>
<tr>
<td>C7</td>
<td>$1.4 \pm 0.2$</td>
<td>$1.48^{+0.05}_{-0.04}$</td>
<td>...</td>
<td>273.1/245</td>
</tr>
<tr>
<td>C8</td>
<td>$1.6^{+0.3}_{-0.2}$</td>
<td>$1.54^{+0.06}_{-0.05}$</td>
<td>...</td>
<td>203.6/203</td>
</tr>
<tr>
<td>C9</td>
<td>$1.2^{+0.6}_{-0.5}$</td>
<td>$1.4 \pm 0.1$</td>
<td>...</td>
<td>65.9/69</td>
</tr>
<tr>
<td>C10</td>
<td>$1.0^{+0.7}_{-0.5}$</td>
<td>$1.5 \pm 0.2$</td>
<td>...</td>
<td>32.4/20</td>
</tr>
<tr>
<td>C11</td>
<td>$1.0 \pm 0.5$</td>
<td>$1.5 \pm 0.1$</td>
<td>...</td>
<td>89.3/94</td>
</tr>
</tbody>
</table>

*The short observation ID as defined in Table 1.
$^b$ $N_H$ frozen at $1 \times 10^{21}$ cm$^{-2}$.

The data spectra of the source from XMM-Newton observation X2 (green – only EPIC-pn data is shown for clarity), Chandra observation C6 (black) and combined FPMA and FPMB data from NuSTAR (blue), along with the NuSTAR background spectrum (blue crosses). We detect a good signal from NuSTAR up to $\sim 20$ keV.

While both observations are consistent with a cut-off to the energy spectrum at 18 keV, we find that a cut-off power-law model offers no improvement over a power-law model for either observation X2 or C6. This is not entirely unexpected, as the appearance of a turnover is mainly driven by a single NuSTAR data point. Further observations with NuSTAR simultaneous with observations from XMM-Newton are required to better constrain the high-energy spectral shape of this source.

3.2 Timing Analysis

All observations of ULX-7 with XMM-Newton are flagged as variable in the XMM-Newton Serendipitous Source Catalogue, and all have fractional rms at $\sim 30\%-40\%$ according to an initial examination of the light curves using the LCSTATS routine in FTOOLS. Previous studies have attempted to find a period in this variability, with Liu et al. (2002) suggesting a period of 7620 s using EFSEARCH and Dewangan et al. (2005) similarly declaring a period of 5925 s with $\sim 26$ significance. However, a subsequent study by Terashima, Inoue & Wilson (2006) found no evidence of periodic variation, instead suggesting that the source variability is due to stochastic noise.

The source also undergoes significant long-term variation, with the dynamic range of its flux encompassing well over an order of magnitude, even over the course of a single month when observed using Chandra in 2012. The long-term lightcurve, along with an example of short-term variability from observation X3, is shown in Fig. 7. However, despite this variation in flux there is no

The fit parameters with NuSTAR data included are given in Table 4, although it is important to note that neither of these observations are contemporaneous with the NuSTAR observation and so we cannot be certain that the source is in the same spectral state between them.

While both observations are consistent with a cut-off to the energy spectrum at 18 keV, we find that a cut-off power-law model offers no improvement over a power-law model for either observation X2 or C6. This is not entirely unexpected, as the appearance of a turnover is mainly driven by a single NuSTAR data point. Further observations with NuSTAR simultaneous with observations from XMM-Newton are required to better constrain the high-energy spectral shape of this source.
evidence for a flux-hardness relation, given the consistent shape of the spectrum found in Section 3.1.

We created power spectra for the XMM-Newton and Chandra observations of ULX-7 by taking the periodogram of fixed-length segments in each observation taken from good time intervals and averaging over all segments for each telescope. We used 3200 s segments for the XMM-Newton observations and 12800 s segments for the Chandra observations. The greater length of the Chandra observations allows us to probe down to $\sim 10^{-3}$ Hz, although at higher frequencies the data is dominated by noise, whereas the XMM-Newton data, while not having the low-frequency range, has far less contribution from white noise up to $\sim 8 \times 10^{-3}$ Hz. The two datasets are therefore very complementary and allow us access to two decades of frequency space.

The power spectra are normalised so that the power is given in units of the squared fractional rms per frequency interval. We combined all observations for each telescope, given that the overall shape of the power spectrum remained consistent from observation to observation, except for Chandra observations C4 and C5, which did not have good time intervals long enough for our chosen segment length, and C12, which contributed a lot of noise to the power spectrum due to a very low count rate.

We first rule out a simple power-law shape to the power spectrum by performing a simultaneous fit to the XMM-Newton and Chandra data using the whittle statistic in XSPEC and a powerlaw model, disregarding frequency bins consistent with the white noise level of the power spectrum. The best-fitting power-law has $\alpha = 0.4$ (for $P(\nu) \propto \nu^{-\alpha}$) which has $\chi^2 = 54.8/28$ and we reject at $> 3\sigma$ significance, so we can be confident that the power spectrum shape requires a more complex model to fit. We next fit the power spectrum with a broken power-law model. This is an excellent fit to the data, with goodness-of-fit $\chi^2 = 23.0/25$, however the fit parameters are not highly constrained. We find that the power spectrum exhibits a break at $\nu_b = 6.5^{+0.5}_{-1.1} \times 10^{-4}$ Hz, with a low-frequency slope of $\alpha_1 = -0.1^{+0.5}_{-0.2}$ and a high-frequency slope of $\alpha_2 = 0.65^{+0.05}_{-0.14}$ (errors were found using a Monte Carlo Markov Chain method with a chain length of 100,000). Since the break is at the overlap of the two power spectra and its frequency can only be constrained with the Chandra data, it is likely that future long observations with XMM-Newton will help to better characterise the break. The power spectra for the two telescopes are shown in Fig. 8.

Figure 6. Spectra of ULX-7 from XMM-Newton observation X2 and Chandra observation C6, unfolded from the detector response and plotted between 0.3 and 10 keV, with the combined FPMA and FPMB data from NuSTAR plotted between 3 and $\sim 20$ keV (blue). XMM-Newton spectra colours are as Fig. 4. Top left, X2 and NuSTAR data, fitted with a mekal+mekal+tbabs*powerlaw model. Top right, C6 and NuSTAR data, fitted with a tbabs*powerlaw model. Bottom left, X2 and NuSTAR data, fitted with a mekal+mekal+tbabs*cutoffpl model. Bottom right, C6 and NuSTAR data, fitted with a tbabs*cutoffpl model.

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In order to see how the fractional variability of ULX-7 changes as a function of energy, we created a fractional rms spectrum using five energy bands by integrating over the power spectrum for each energy band, averaging over all XMM-Newton segments. Since the source flux is contaminated by diffuse emission, giving the intrinsic fractional variability of ULX-7 is the third ULX to date for which a positive linear rms-flux relation has been confirmed (Hernández-García et al. 2015).

Finally, we also examine the data from the XMM-Newton EPIC-pn camera, which has a time resolution of 73.4 ms in full-frame mode, for evidence of coherent pulsations such as those produced by pulsars. To do this we use the H-test (de Jager, Rauhut, & Swanepoel 1989). In brief, the H-test is a test for a periodic signal that is especially useful in the case where there is no a priori information about the shape of the light curve available. The H statistic is based on the $Z_m^2$ statistic (Buccheri et al. 1983), and defines the optimal number of harmonics, $M$, such that:

$$H \equiv \max_{1 \leq m \leq 20} (Z_m^2 + 4m + 4) = Z_M^2 + 4M + 4 \geq 0$$

We apply the $H$-test to the five longest XMM-Newton observations, examining a range of frequencies from 6.85 Hz (approximately the Nyquist frequency for EPIC-pn data) to 0.1 Hz. We found no evidence of a pulsation period to high significance (that is, the commonly quoted condition of $H > 23$), although we found three marginally significant periods with a significance of $> 10\sigma$ for a positive slope. The rms-flux relations are shown in Fig. 10. ULX-7 is the third ULX to date for which a positive linear rms-flux relation has been confirmed (Hernández-García et al. 2015).

**Figure 7.** Top, the long-term lightcurve for ULX-7 showing the 0.3–10 keV flux over time as measured using the XMM-Newton and Chandra telescopes. Points identified as PIMMS are fluxes calculated from the count rate assuming a power-law spectrum with $N_1 = 1 \times 10^{31}$ cm$^{-2}$ and $\Gamma = 1.5$. See Table 1 for details and values. Bottom, a 10 ks segment of the pn + MOS light curve of observation X3, binned into 50 s intervals.

**Figure 8.** The power spectra for Chandra (top) and XMM-Newton (bottom) observations, along with the best-fitting broken power-law model in blue (for which $v_1 = 6.5 \times 10^{-3}$ Hz, $\alpha_1 = -0.1$ and $\alpha_2 = 0.65$), normalised so that power is in units of the squared fractional rms per frequency interval. The white noise level is marked by the dashed grey line, and the bins discounted from analysis due to being dominated by white noise are also coloured grey. The data is geometrically rebinned with a co-efficient of 1.1, and error bars represent the standard error on the mean for each frequency bin.
probability of $p < 10^{-3}$ that these $H$ values were produced by chance, which are listed in Table 5. It should be noted that a period of 0.3003 s is approximately 4 times the time resolution of the EPIC-pn camera.

### 3.3 Optical Counterparts

We mark the Chandra position of ULX-7 on a true color HST image with a 0.6 arcsecond radius 90% confidence circle in Fig. 11. Using DAOPHOT II, we were able to obtain photometric data for 11 objects within the circle, although visual inspection reveals that there are other possible counterparts that are too faint or unresolved to characterise. A list of objects and their magnitudes as determined by DAOPHOT II is given in Table 6. Given the faint and crowded nature of the field, we do not expect the values we obtain to be more than approximations.

Using the distance modulus for M51, $\mu = 29.45$, we can calculate an absolute magnitude for each object. We plot $M_V$ against the $B - V$ colour in Fig. 12. Most of the objects that we are able to characterise have low absolute magnitudes (that is, high luminosities) and $B - V$ colours consistent with OB supergiants (Roberts, Levan & Goad 2008) – suitable companion stars for a HMXB – for which we would expect values of $M_V$ of between $-7$ and $-4$, and $B - V \sim -0.2$ (Wegner 2006; Roberts, Levan & Goad 2008). This appears to be consistent with previous findings indicating that ULX optical counterparts are often consistent with being OB-type stars (e.g. Gladstone et al. 2013). We might also expect these properties from an X-ray irradiated disc (e.g. Madhusudhan et al. 2008; Tao et al. 2011). The two exceptions are objects 1 and 9, which are significantly brighter and redder than expected for a OB-type star, and too luminous to be red supergiants (for which we would expect $M_V \sim -6$; Heida et al. 2014). Because of this, it is likely that objects 1 and 9 are small, unresolved clusters of multiple stars. This may also be the case for object 2, as it is also unusually bright.

While the colours for the rest of the objects are consistent with OB-type stars, we would also expect background quasars at intermediate redshifts to appear blue, and it would be reasonable to detect them at similar apparent magnitudes to these objects. Therefore we also calculated an X-ray/optical ratio for the objects, using the highest $2-10$ keV flux recorded from ULX-7 and calculating the optical flux using the formula $F_{\text{opt}} = 8 \times 10^{-6} \cdot 10^{-m_V/2.5}$ erg cm$^{-2}$ s$^{-1}$ (e.g. Shtykovskiy & Gilfanov 2005).
These ratios are given in Table 6. For any potential counterpart within the error circle that is not characterised by DAOPHOT II, including the faint red objects for which we were unable to determine a $B$- or $V$-band magnitude, the optical flux would be lower therefore the ratio will be higher. The same applies to the brightest counterparts, for although they have the lowest ratios, they are likely to be collections of less luminous objects which will all individually have higher ratios.

### 4 DISCUSSION

The high luminosity of ULX-7 places it firmly into the category of ULXs, albeit at a luminosity that is not particularly remarkable within that class of sources. What makes ULX-7 remarkable is its unusual spectral and timing properties compared with the majority of ULXs. According to the classification of super-Eddington accretion regimes by Sutton, Roberts & Middleton (2013), sources in the hard ultraluminous regime have very low levels of variability if it is present at all, with high variability only featuring in sources in the soft ultraluminous regime. Middleton et al. (2015a) suggests that the observed spectrum and variability of sources in ultraluminous accretion states depend on the inclination and accretion rate of the source, with the main driver of these differences being a radiatively-driven, massive and inhomogeneous wind, that imprints the variability on the hard component of the spectrum if it rises into the line-of-sight.

The energy spectrum of ULX-7 could be argued to be consis-
tent with a hard ultraluminous accretion regime, with the character-
istic two-component shape expected in the spectrum smeared out
by insufficient data quality, except for a hint of a soft excess from
XMM-Newton observation X3 and a putative high energy turnover
in the NuSTAR data. However, were the source to truly be in this
regime, we would not expect the high levels of variability that we
observe across all observations. This is furthermore unusual given
that variability is high at all observed energies, unlike the observed
higher variability above 1 keV in the soft ultraluminous regime.
Additionally, the observed luminosity of ULX-7 varies by over an or-
der of magnitude, but we see no evidence of the accretion properties
changing. Therefore a soft, clumpy wind is unlikely to be the cause
of this variability.

It is possible that our understanding of the hard ultraluminous
regime of ULXs is as yet incomplete, and that ULX-7 is an un-
usually variable specimen of this accretion mode. However, as the
data quality is insufficient to prefer a more complex spectral model
over a power-law, we have examined other interpretations for the
nature of this object that have power-law-like spectra, in particular
considering the scenarios of a background AGN, a super-Eddington
neutron star and an IMBH.

4.1 Background AGN

An occasional occurrence in studies of ULXs is the discovery that
the object is a background AGN (e.g. Dadina et al. 2013; Sutton
et al. 2015), rather than located within the galaxy it appears coinci-
dent with. The hard power-law spectrum that we observe is not in-
consistent with ULX-7 being an AGN (e.g. Reeves & Turner 2000;
Mateos et al. 2010), so we need to look to other source properties
to confirm its location.

Examining the possible optical counterparts suggests that this
source is likely located within the galaxy. The sources that we are
able to characterise are consistent either with OB supergiant type
stars, or with clusters of cooler stars. While background quasars
at intermediate redshifts could be consistent with the $B - V$ colour
and magnitude, we find that for the OB-type stars the X-ray/optical
ratios are high, with $F_X/F_{opt} > 10$ in all cases. We would expect
the majority of AGNs to have optical/X-ray flux ratios between 0.1
and 10 (e.g. Krautter et al. 1999; Hornschemeier et al. 2001), so it
is unlikely that any of these potential optical counterparts are back-
ground AGNs. We are only able to characterise the very brightest
potential optical counterparts of ULX-7, given the limitations of the
data, but since the X-ray/optical relationship would be even higher
for the fainter objects we cannot characterise, these are even less
likely to be a background AGN.

The X-ray/optical relation alone comes with the caveat that we
only have one epoch of HST data and assume the same optical
flux for the highest X-ray flux observation. If the optical emission
also varies over time, this conclusion does not necessarily hold. It
is also possible that a very highly obscured QSO would have an
extreme X-ray/optical flux ratio. However, the proposal that ULX-
7 is not a background AGN is also supported by the X-ray timing
properties of the source, since there is a high amount of variability
on timescales of $\sim 100$ s. This is shorter than expected for an AGN,
for which noise tends to extend only down to timescales of tens of
minutes to hours (e.g. González-Martín & Vaughan 2012). Addi-
tionally, the low-frequency break feature we see is also not often
seen in AGNs – one exception being Ark 564, which has a break
at $7.5 \times 10^{-7}$ Hz in the 2-8.8 keV band (McHardy et al. 2007), a
much lower frequency than the one we see for ULX-7.

4.2 Neutron Star

Given the recent discovery that M82 X-2 is in fact a highly super-
Eddington pulsar (Bachetti et al. 2014), another possible interpre-
tation for ULX-7’s unusual behaviour may be that it is a neutron
star rather than a BH. To this end, we searched for coherent pulsa-
tions within the XMM-Newton data, but found no strong evidence
for any between 6.85 Hz and 0.1 Hz with significance comparable
to other studies (that is, with $H > 23$). With that said, the absence
of pulsations in an $H$-test does not necessarily mean that there is no
stellar surface – using a similar method, Doroshenko, Santangelo
& Ducci (2015) were unable to detect pulsations from M82 X-2 in
the XMM-Newton data for the source. It could instead mean that
that either the pulsation amplitude was too low to be detected, or
the spin-down rate and/or orbital modulation of the signal is sig-
ificant enough to require an accelerated epoch folding search to
detect pulsations.

The neutron star equivalent to super-Eddington accreting BHs
are Z-sources, the most luminous neutron stars, accreting close to
or above their Eddington limit (Hasinger & van der Klis 1989). They
can also exhibit high amounts of variability, although at very low
frequencies their power spectra exhibit a steep power-law shape with $\alpha \sim 1-2$, inconsistent with the power spectrum of ULX-
7, which exhibits a low break and a flatter slope. A comparison
with the very luminous extragalactic Z-source LMC X-2 further re-
veals that its energy spectrum is harder than that of ULX-7 as well
(Barnard et al. 2015), so the properties of ULX-7 appear to be in-
consistent with what we would expect from Z-sources.

However, the recently-reported spectral properties of M82 X-
2 (Brightman et al. 2015) indicate that it is possible for a super-
Eddington neutron star ULX to show similar properties to ULX-7.
As well as long-term flux variations over two orders of magnitude,
examination of the pulsed spectrum in NuSTAR shows that the spec-
trum of M82 X-2 has a high energy turnover at $14.3 \pm 3$ keV. Further
observations using NuSTAR would help to confirm whether ULX-7
exhibits a similar spectral shape at high energies.

4.3 Intermediate Mass Black Hole

Another possible interpretation is that ULX-7 is instead a BH ac-
creting in a hard state analogous to lower luminosity BHs. This
would imply an unusually high BH mass due to its high luminosity,
despite a low assumed accretion rate, and would manifest a hard
power-law shaped spectrum with high variability across all energy
bands (e.g. Grinberg et al. 2014) like we see in ULX-7. The irra-
diated disc of an IMBH would also be consistent with most of the
possible optical counterparts we detect (Madhusudhan et al. 2008).

This interpretation is supported by the presence of a break in
the power spectrum from a spectral index of $\alpha \sim 0$ to $\alpha \sim -1$,
a feature that we would expect from the low-frequency break in
the power spectrum of a source in the hard state, which can be
modelled by two Lorentzians or, more simply, a doubly-broken
power-law (e.g. Done & Gierliński 2005), whose high-frequency
break scales with the BH mass. While we see no evidence of a
high-frequency break, we can take the lower limit of such a break
to be the white noise level of the XMM-Newton power spectrum,
at $v_b \sim 9 \times 10^{-3}$ Hz. We can use the relationship between high-
frequency break and BH mass found to apply to BHs of all size
bands by McHardy et al. (2006), with the offset for BHs in the
hard state from Kording et al. (2007), to calculate an upper limit on
the BH mass using the following equation: $\log v_b = 0.98 \log M -
2.1 \log M_{BH} - 15.38$. We calculate $M$ from $L_{bol}/\eta c^2$, assuming an
accretion efficiency of $\eta = 0.1$ for the highest-flux observation, and
obtain $L_{\text{bol}}$ by applying a bolometric correction of 5 to the 2–10 keV luminosity of that observation (Körding, Fender & Migliari 2006). In this way, we find an upper limit of $M_{\text{BH}} < 1.6 \times 10^3 \, M_\odot$, which means that ULX-7 is consistent with being an IMBH.

We would expect an IMBH accreting in the hard state to also exhibit radio emission from a jet. Since there is no radio detection of ULX-7, we can use the calculated density upper limit of $7 \times 10^{-4} \, \mu \text{Jy beam}^{-1}$ to establish an upper limit on the BH mass independent of that calculated from the timing analysis, using the fundamental plane in BH mass, radio, and X-ray luminosity which has been found to apply to BHBs and AGNs as well as intermediate sources (e.g. Mezcua et al. 2015). We use the fundamental plane equation described in Gültekin et al. (2009), which has been calibrated for low mass AGNs in the range $10^3 - 10^5 \, M_\odot$ (Gültekin et al. 2014), and assume a flat radio spectral index of $\alpha = 0.15$ to find $L_{\text{GHz}}$. We calculate a mass upper limit of $M_{\text{BH}} < 3.5 \times 10^4 \, M_\odot$, which also allows for an IMBH interpretation.

It is also possible to place a lower limit on the BH mass of an IMBH by taking the maximum observed flux of $8.6 \times 10^{-13} \, \text{erg cm}^{-2} \, \text{s}^{-1}$ and assuming a maximum accretion rate for the low/hard state, given that ULX-7 is a persistent source. The maximum luminosity of a low/hard state tends to be $\sim 2\%$ of Eddington\(^5\), with the highest Eddington ratios observed being $\sim 5\%$ (Maccarone 2003). Therefore we use an Eddington ratio of $5\%$ to place a lower limit on the black hole mass of $M_{\text{BH}} > 1.0 \times 10^5 \, M_\odot$, which is consistent with our previously calculated upper limits and places the source firmly within the IMBH regime.

We can compare our results for ULX-7 with HLX-1, currently the best candidate for an IMBH due to its extreme luminosity and evidence of state transitions. When first discovered, it had a spectrum consistent with an absorbed power-law (Farrell et al. 2009), albeit a softer one than we see in ULX-7. Further studies have revealed it to have a very high dynamic range, as we see for ULX-7, although its spectrum changes shape and it appears to demonstrate state transitions (Godet et al. 2009) whereas ULX-7 appears to remain in a single state. In its third XMM-Newton observation, HLX-1 appeared to enter a hard state, with a lower luminosity and a spectral index of $\Gamma = 1.6 \pm 0.4$ when compensating for the host galaxy’s contribution to the soft emission and fitted alongside an accretion disc (Servillat et al. 2011). No significant intrinsic variability was detected, although since the power was not well constrained, a high fractional variability was not ruled out. Additionally, there have also been radio detections of HLX-1 while in this state (Cseh et al. 2015), making it analogous to the hard state seen in stellar-mass BHBs.

From this, we can conclude that it is reasonable to suggest that ULX-7 could also be an IMBH in a hard state, its large mass being the cause of its high luminosities, although unlike HLX-1, it does not appear to undergo state transitions as it changes luminosity.

The association of ULX-7 with a young stellar population implies that it is a short-lived source if it was formed there (Roberts 2007), and in this respect it bears similarity to the wider ULX population which is found predominantly in star-forming regions. This would be a point in favour of a more standard stellar remnant ULX interpretation. However, there are possible formation scenarios for an IMBH in a young stellar environment. For example, an IMBH could have formed through runaway mergers within a dense stellar cluster and subsequently been ejected, or the cluster dissipated into the disc of the galaxy, leaving the IMBH accreting within a dense molecular cloud (e.g. Miller & Hamilton 2002) or retaining a young stellar population around itself (e.g. Farrell et al. 2012). This is an unlikely formation scenario for the ULX population as a whole (King 2004), but still a possibility for an individual object, as a very rare occurrence.

Another possibility is a minor merger of a dwarf galaxy with the main galaxy, a mechanism that has been suggested for HLX-1 (Farrell et al. 2012; Mapelli, Zampieri & Mayer 2012) and NGC 2276-3c (Mezcua et al. 2015). A recent minor merger could be identified by evidence of disruption in the spiral arm around the source and increased levels of star formation, however these are seen in the northern spiral of M51 anyway due to M51a’s interaction with M51b. Therefore any evidence for a minor merger that could have formed ULX-7 would likely be eclipsed by the disruption of the current interaction.

\section{5 CONCLUSIONS}

We have undertaken a case study of M51 ULX-7, a source with moderate luminosity and very high variability for a ULX, and a consistently hard spectrum. This is in contrast to expected ULX variability behaviour, in which we might expect to see high variability in sources with soft spectra. We find that the source is generally well-fitted by a power-law with a spectral photon index that remains steady at $\Gamma \sim 1.5$ while the source luminosity varies by over an order of magnitude over the course of 12 years. ULX-7 also demonstrates very high fractional variability between 0.3 and 10.0 keV, with a broken power-law shape to its power spectrum analogous to the low-frequency break in the power spectrum of an X-ray binary accreting in the hard state. We find solid evidence for a positive linear rms-flux relation, making ULX-7 the third ULX for which this feature is confirmed. We find no evidence of coherent pulsations, however.

Taken together, these properties are unusual for a ULX, and are suggestive of an alternative explanation to the broadened disc or ultraluminous regimes that describe the majority of ULXs for which we have reasonable data (Gladstone, Roberts & Done 2009; Sutton, Roberts & Middleton 2013). By examining the possible optical counterparts in \textit{HST}, we consider it unlikely that this source is a background AGN. The lack of pulsations and dissimilarity to Z-source properties imply that it is not a neutron star either, although it may possibly bear similarities to the properties of the neutron star ULX M82 X-2.

Our results are consistent with ULX-7 being an IMBH accreting in the hard state. Using the absence of a high-frequency break and a radio detection, we can calculate upper limits on the BH mass of $M_{\text{BH}} < 1.55 \times 10^3 \, M_\odot$ and $M_{\text{BH}} < 3.5 \times 10^3 \, M_\odot$ respectively, and by taking the maximum accretion rate to be 5\% of the Eddington limit, we can calculate a lower mass limit of $M_{\text{BH}} > 1.0 \times 10^3 \, M_\odot$. All of these limits show the source to be consistent with an IMBH interpretation if we assume it is accreting in the hard state. There remains weak evidence of a possible high energy turnover in the spectrum when considering the NuSTAR data on this source, which would imply that this source may instead be exhibiting some permutation of the ultraluminous state after all, but simultaneous deep observations with \textit{XMM-Newton}...
and NuSTAR will be required to confirm or rule out the existence of these features.

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