Strong constraints on a super-Eddington accretion flow: XMM–Newton observations of an intermediate-mass black hole

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ABSTRACT
RX J1140.1+0307 is a Narrow Line Seyfert 1 (NLS1) with one of the lowest black hole masses known in an AGN ($M \lesssim 10^6 M_\odot$). We show results from two new XMM–Newton observations, exhibiting soft 2–10 keV spectra, a strong excess at lower energies, and fast X-ray variability which is typical of this class of AGN. The soft excess can be equally well fit using either low-temperature Comptonization or highly smeared, ionized reflection models, but we additionally consider the fast X-ray variability to produce covariance, lag and coherence spectra to show that the low-temperature Comptonization model gives a better description of the break in variability properties between soft and hard X-rays. Both these models require an additional component at the softest energies, as expected from the accretion disc. However, standard disc models cannot connect this to the optical/UV emission from the outer disc unless the mass is underestimated by an order of magnitude. The variable optical and far UV emission instead suggests that $L/L_{\text{Edd}} \sim 10$ through the outer disc, in which case advection and/or wind losses are required to explain the observed broad-band spectral energy distribution. This implies that the accretion geometry close to the black hole is unlikely to be a flat disc as assumed in the recent X-ray reverberation mapping techniques.

Key words: accretion, accretion discs – galaxies: nuclei – galaxies: Seyfert – X-rays: galaxies.

1 INTRODUCTION
Intermediate-mass black holes (IMBH), in the range $10^4$–$10^6 M_\odot$, are of particular interest because this population would fall within the gap between the two principal black hole (BH) populations, i.e. supermassive black holes (SMBH) with $M \gtrsim 10^6 M_\odot$ and stellar mass BHs with $M \sim 10 M_\odot$. Currently, there are very few well-studied IMBH. Two examples are NGC 4395 (Filippenko & Ho 2003) and POX 52 (Kunth, Sargent & Bothun 1987; Barth et al. 2004).

Over two decades, the most robust technique to measure BH masses in active galactic nuclei (AGN) has been the reverberation mapping (RM) technique, which estimates the radius of the broad-line region (BLR) by measuring the time lag between the line emission from the BLR and the intrinsic continuum emission from the accretion disc. Since optical RM requires well-sampled spectroscopic monitoring of variable AGN over months and years, the total number of sources with RM masses is currently less than 40 (e.g. Kaspi et al. 2000; Peterson et al. 2004, 2005; Denney et al. 2006; Bentz et al. 2009b; Du et al. 2014). Alternatively, the RM measurements can be used to derive a radius–luminosity relation which can then provide BH mass based on single epoch measurements using the Balmer line width (normally the FWHM of H β) and the luminosity (generally the monochromatic luminosity at 5100 Å, hereafter $\lambda L_{5100}$ e.g. Bentz et al. 2006, 2009a; Denney et al. 2010).

By employing this method, Greene & Ho (2004) identified 19 IMBH in the Sloan Digital Sky Survey (SDSS) data base. Following this work, Dong et al. (2007) and Greene & Ho (2007) extended the IMBH sample to include several hundred sources.

RX J1140.1+0307 (hereafter RX1140), also referred to as GH 08 or SDSS J114008.71+030711.4, is amongst the original 19 IMBH sample of Greene & Ho (2004). It has a redshift of 0.081 (comoving distance of 336 Mpc). The SDSS and Hubble Space Telescope (HST) images show a resolved galactic disc component, plus a bar and unresolved nuclear component (Greene, Ho & Barth 2008).

The FWHM of H β measured from the SDSS spectrum is 700–780 km s$^{-1}$ (Ai et al. 2011; Jin et al. 2012a). However, to obtain a BH mass also requires $\lambda L_{5100}$. Determination of this is made more difficult by the presence of contamination from the host galaxy. Deconvolution of the HST image gives an estimated AGN continuum of $\lambda L_{5100} \sim 6 \times 10^{42}$ ergs$^{-1}$, which is lower than the observed variable flux of $\lambda L_{5100} \sim 8 \times 10^{42}$ ergs$^{-1}$ (Rafter et al. 2011). This gives a BH mass of $8–10 \times 10^5 M_\odot$ (Greene et al. 2008; Ai et al.
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So this directly measures the mass accretion rate provided the BH
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was selected from a nearby circular region with the same radius as for the source. For Obs-1, the net source count rates are 0.62, 0.13 and 0.13 ct s$^{-1}$ for the PN, MOS1 and MOS2, respectively. Obs-2 has a mean count rate that is half that of Obs-1. Obs-3 has a similar mean count rate as Obs-1. All of these count rates are well below the threshold count rates capable of causing photon pile-up effects when using the full window mode of the EPIC cameras.

We selected data with PATTERN $\leq$ 12 for MOS1 and MOS2, and PATTERN $\leq$ 4 for the PN. Light curves were extracted from both the source and background regions. There were high-background flares during all three observations. Therefore, we visually checked the background and source regions. There were high-background flares when using the full window mode of the EPIC cameras. The threshold count rates were set to the mean spectral model, renormalized to the 2–10 keV count rate.

Over longer time-scales, the spectral shape changes. The upper panel of Fig. 3 a shows the time-averaged spectrum of Obs-1 (black). The fast variability seen in Fig 1a does not significantly change the spectral shape. We select based on intensity to construct a high ($pn_{rate} \geq 0.7$ ct s$^{-1}$; orange) and low ($pn_{rate} \leq 0.35$ ct s$^{-1}$; blue) count rate spectra from Obs-1. These are identical within errors to the mean spectrum. This can be seen in the lower panels of Fig. 3a, which gives the ratio of each data set to the mean spectral model, renormalized to the 2–10 keV count rate.

Over longer time-scales, the spectral shape does change. The upper panel of Fig. 3 b compares the time-averaged X-ray spectra for Obs-1 (black) and Obs-2 (red). The mean spectrum of Obs-3 is almost identical to Obs-1, and so it is not shown in the figure. A ratio of the best-fitting model to Obs-1 (black solid model) rescaled to the observed 2–10 keV spectrum of Obs-2 (red solid model) significantly underpredicts the soft emission, as can be seen also in the lower panel which gives the ratio of each data set to the model.

3 THE VARIABILITY STUDY

The background-subtracted PN light curves over the total energy band (0.3–10 keV) are shown in Fig. 1. Strong variability is observed on all time-scales. This is confirmed by inspection of the power spectral density (PSD) in Fig. 2. The flat PSD indicates that intrinsic variability (i.e. Poisson noise subtracted) exists across the 0.2–10 ks time-scale. None of the observations show any sign of a high-frequency break. This is clearly different from the case of PG 1244+026, where the 0.3–1 keV power spectrum drops substantially above $\sim 10^{-3}$ Hz (Jin et al. 2013), strongly suggesting that RX1140 has a substantially lower BH mass than PG 1244+026, and that the BH mass is around $\lesssim 10^6 M_\odot$ (Ponti et al. 2012; Kelly et al. 2013; Ludlam et al. 2015).

The upper panel of Fig. 3 a shows the time-averaged spectrum of Obs-1 (black). The fast variability seen in Fig 1a does not significantly change the spectral shape. We select based on intensity to construct a high ($pn_{rate} \geq 0.7$ ct s$^{-1}$; orange) and low ($pn_{rate} \leq 0.35$ ct s$^{-1}$; blue) count rate spectra from Obs-1. These are identical within errors to the mean spectrum. This can be seen in the lower panels of Fig. 3a, which gives the ratio of each data set to the mean spectral model, renormalized to the 2–10 keV count rate.

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3.1 The RMS Spectra

The fractional variability observed in different energy bins, i.e. the RMS spectra (e.g. Edelson et al. 2002; Markowitz, Edelson & Vaughan 2003; Vaughan et al. 2003), can be very useful in decomposing the different spectral components. We use the segment algorithm described in Wilkinson & Uttley (2009) to calculate the RMS. For every energy bin, the light curve is divided evenly into several segments. Then the excess variance is calculated for every segment and averaged over all segments. The square root of the excess variance is the RMS. The error bars are calculated using equation B2 in Vaughan et al. (2003). The binning time and segment length determine the time-scale for which the RMS is calculated. The occurrence of intervals of high-background interrupt the continuity of the light curve. In Obs-3, the longest continuously sampled segment is only 11 ks, whereas it is longer in Obs-1 and Obs-2. In order to mitigate any bias introduced by high-background contamination, we choose a longest time segment of 11 ks, and we can identify a total of eight segments all with little high background, i.e. three segments in Obs-1, three in Obs-2 and two in Obs-3 (see the cyan regions in Fig. 1).

1 http://heasarc.gsfc.nasa.gov/FTP/xmm/data/responses/om

Figure 1. The 100 s binned, background subtracted, 0.3–10 keV light curves for Obs-1, Obs-2 and Obs-3. Each cyan region is a 11 ks segment that is free from high-background contaminations.
Figure 2. PSD for the 0.3–10 keV light curves of the three observations obtained using ftool powspec after subtracting the Poisson counting noise. For Obs-3, only the two 11 ks segments in Fig. 1 were used to avoid the influence of high background.

Figure 3. Panel a: time-averaged spectra of Obs-1 (black), together with the high count rate (\( pn_{rate} \geq 0.7 \text{ ct s}^{-1} \); orange) and low count rate (\( pn_{rate} \leq 0.35 \text{ ct s}^{-1} \); blue) spectra seen within Obs-1. The best-fitting model of Obs-1 is the same as in Fig. 5a, then renormalized to match the 2–10 keV of each spectrum. The lower panel shows the ratio of each data set to the model. Panel b: time-averaged spectra of Obs-1 (black) and Obs-2 (red), there is significant spectral variability in Obs-2, where the soft X-rays are weaker.

3.2 The covariance spectra

The RMS variability spectrum shows all variability at each energy, but there may be multiple components. A more powerful technique is to produce a covariance spectrum (developed by Wilkinson & Uttley 2009), as this determines the spectrum of the variability correlated with a given energy band light curve used as a reference. For the NLS1 PG 1244+026, Jin et al. (2013) showed that using the fastest variability observed in the hard X-ray (2–10 keV) light curve as a reference band, gave strong evidence for a Comptonization origin for the soft X-ray excess, while using the fastest variability with much less difference between the fast variability as a function of energy (more HF power below 1 keV, and marginally less at the highest energies). Whatever process occurred to depress the soft spectrum relative to the mean (Fig. 3b) may also have increased its fast variability (see Gardner & Done 2015 for a possible explanation of this in terms of cloud occlusion in the inner disc).

There are insufficient data to produce frequency-resolved RMS spectra. Instead, we calculate only RMS of the high-frequency (HF) variability using time-scales of 0.2–2 ks extracted from those eight segments. The results are shown in Fig. 4. Interestingly, the HF RMS spectra reveal a rising shape from the soft to hard X-ray ranges in Obs-1 and Obs-3. This is similar to that observed in some other high-mass accretion rate NLS1s, such as PG 1244+026 (Jin et al. 2013), RE J1034+396 (Middleton et al. 2009) and RX J0136.9–3510 (Jin et al. 2009). This difference in variance between soft and hard energy bands can be explained if the soft X-ray excess varies less than the power-law tail, so favouring models where this is a true additional component e.g. from soft Comptonization (e.g. Gierliński & Done 2004, Middleton et al. 2009, Jin et al. 2013, Matt et al. 2014) rather than due to ionized, smeared reflection, as this tends to contribute equally in the soft and hard bands (Gierliński & Done 2006).

Another important feature seen in Fig. 4 is that the 0.3–1 keV HF RMS in Obs-2 is rather different to what is seen in Obs-1 and Obs-3,
observed in the 0.3–1 keV band showed evidence for a contribution at the lowest energies from the disc.

Here we apply the same technique to our data sets to produce the HF (0.2–2 ks) covariance spectra for hard (2–10 keV) and soft (0.3–1 keV) X-rays as the reference band. We use only the PN detector data so as not to introduce differences in the responses from combining data from the PN and MOS. The data quality means that the signal to noise of the covariance spectra for RX1140 is much lower than for PG 1244+026. Then we study both the covariance spectra and the time-averaged spectrum (see Fig. 5) in order to constrain the origin of the soft excess, i.e. whether it can be better fit by an additional Comptonization model or by relativistically smeared reflection, and whether there is an additional contribution from the accretion disc itself.

4 SPECTRAL ANALYSIS

The X-ray spectrum derived from Obs-1 has been analysed previously by Miniutti et al. (2009). They found that an X-ray reflection plus a thermal disc model gives a better fit than the smeared absorption model. Ai et al. (2011) found that reflection and Comptonization models gave comparably good fits, and that both of these were better than smeared absorption and p-free disc models. The shape of the HF RMS and mean spectra in Fig. 3 and Fig. 4 also indicates that RX1140 may be similar to other extreme NLS1s such as PG 1244+026, RE J1034+396 and RX J0136.9−3510, whose soft X-ray excess can be well interpreted using the Comptonization model. Therefore, we try fitting both the Comptonization and reflection models for the Obs-1 and Obs-2 spectra. The time-averaged spectrum of Obs-3 is identical to that of Obs-1, but Obs-1 has better data quality than Obs-3 because of its lower background. Therefore, we only present spectra extracted from Obs-1 and Obs-2. The best-fitting models are shown in Fig. 5.

4.1 Comptonization model

For the Comptonization scenario, we use a low-temperature, optically thick Comptonization model (comptt model, Titarchuk 1994; Hua & Titarchuk, 1995; Titarchuk & Lyubarskij 1995) to fit the soft X-ray excess; a high-temperature Comptonization (nthcomp model in XSPEC; Zdziarski, Johnson & Madej 1996; Zycki, Done & Smith 1999) to fit the power-law tail, together with its neutral, smeared reflection (kdblur*pexmon, Laor 1991; recoded as a convolution model, Nandra et al. 2007). We also include an accretion disc component (diskbb model, Mitsuda et al. 1984; Makishima et al. 1986). Using the equation in Peterson (1997) and assuming $r_{in} = 6r_g$, $Log(M) = 5.77$ and $L/L_{Edd} = 2.69$ (Miniutti et al. 2009), we calculate the temperature at the inner radius ($T_{in}$) to be 110 eV. Including a colour temperature correction would increase this, while allowing for some of the inner disc power to be dissipated into the soft and hard X-ray Compton components would decrease it, so we freeze the parameter $T_{in}$ at this temperature. This also serves as the temperature of the seed photons for both soft and hard X-ray Comptonization components. We fix the Galactic column at $N_H = 1.91 \times 10^{20} \text{cm}^{-2}$ (Kalberla et al. 2005) but allow for some additional free absorption by a gas column in the host galaxy ($zwabs$, Morrison & McCammon 1983). The parameters for the complete XSPEC model are given in Table 1.

While there is some degeneracy between the disc and soft Comptonization components, the presence of a disc component is strongly favoured by this model when fitting the data. In the 0.3–10 keV band, stepping the disc normalization down to zero changes $\chi^2$ from 0.95 to 1.00, and gives $\Delta \chi^2 = 17$ for one free parameter (note: the disc temperature is fixed in the model). In the 0.3–0.5 keV band (consisting of 37 spectral bins), the same test changes $\chi^2$ from 1.26 to 1.44, and gives $\Delta \chi^2 = 7$ for one free parameter.

The HF variability is likely to originate mainly from the inner regions of the flow, where the hard X-ray emission is produced. Hence, we expect that the spectrum correlated with the HF 2–10 keV variability should have the same shape as the high-temperature Comptonization component which dominates the 2–10 keV spectrum in this model. However, reflection (and associated thermal reprocessing which could contribute to the soft X-ray excess: Gardner & Done 2015), should also vary in a correlated manner as the expected reverberation time-scale (Fabian et al. 2009) is short for a low-mass BH. Only the disc component is not expected to show any variability on these time-scales.

To perform spectral fitting, we first applied the spectral model to the entire 0.3–10 keV spectrum, but we found some parameters were not well constrained because of parameter degeneracy. Therefore, we attempt to constrain the hard X-ray Comptonization and neutral reflection components by applying them only to the 2–10 keV

![Figure 4](http://mnras.oxfordjournals.org/)

**Figure 4.** The HF (0.2–2 ks) RMS spectra for the three observations. Obs-1 and Obs-3 have similar fast spectral variability as well as similar mean spectra, while Obs-2 has more fast variability at low energies than both Obs-1 and Obs-3.
The spectra of Obs-1 and Obs-2. The model fits the 2–10 keV spectra well ($\chi^2 = 84/82$). The hard X-ray photon index ($\Gamma$) is found to be $2.26 \pm 0.12$, the inner radius parameter ($R_{in}$) of kdblur is $20_{-18}^{+38}$ with reflection solid angle $\Omega/2\pi$ fixed at unity. Removing the neutral reflection component leads to $\Gamma = 2.13 \pm 0.12$, but the fitting statistics are only slightly worse ($\chi^2 = 96/84$). The low signal-to-noise in the hard X-ray band cannot constrain this reflection component well. Then we refit the model to the entire 0.3–10 keV band by fixing $\Gamma$ at 2.26 and $R_{in}$ at 20, and all spectral components are better constrained than before. The best-fitting parameters are listed in Table 1.

In Obs-1, the HF covariance spectrum can be well fitted by the hard Comptonization with $\Gamma = 2.26$, without significant contribution from a variable soft Comptonization component. On the contrary, the HF covariance spectrum in Obs-2 is softer and so requires more contribution from the soft Comptonization (Fig. 5a and b). Neither covariance spectrum requires any disc component.

### 4.2 The reflection model

Ionized, strongly smeared disc reflection plus a thermal accretion disc component was previously claimed to be a good model for the time-averaged Obs-1 spectrum of RX1140 (Miniutti et al. 2009; Ai et al. 2011). Thus, we use diskbb + nthcomp + kdblur * nthcomp as our spectral model, with $T_m$ of the disc component fixed at 110 eV as before. Fig. 5c and d shows this model applied to Obs-1 and Obs-2, respectively. Again, the low statistics mean that some parameters cannot be well constrained.

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**Figure 5.** X-ray spectral fitting of Obs-1 (Panel Compt-Obs1, Refl-Obs1) and Obs-2 (Panel Compt-Obs2, Refl-Obs2). The upper row shows the results of Comptonization fitting to the mean (red) and HF covariance (blue) spectra. In each panel, red solid line is the best-fitting model, red dashed line is the hard X-ray Comptonization component, red dotted line is the soft X-ray Comptonization component, red dash–dotted line is the hot accretion disc component. The blue lines are spectral fits to the HF covariance spectra with only the soft and hard Comptonization components. The lower row panels present the results of reflection model fitting. The red dashed line is the intrinsic hard Comptonization component, the red dotted line is the reflected component by accretion disc, the red dash–dotted line is the accretion disc component. The blue lines are spectral fits to the covariance spectra with only the hard Comptonization and reflection components.
constrained. We choose to fix the illumination index of the smeared reflection at 5, and fit for the inner disc radius. This is always small in this model, at ∼3–5R_e, so any reverberation time-scale should be short. Hence, both the high-temperature Comptonization and its reflection should vary together. However, the relatively flat HF covariance spectrum in Obs-1 favours a smaller reflection component contribution than in the time-averaged spectrum, while the softer HF covariance spectrum in Obs-2 favours a larger reflection contribution. But again the poor signal to noise means that this is not very significant (Table 1). Similar to what was found using the Comptonization soft excess fits, the accretion disc component is not detected in the HF covariance spectra.

4.3 The lag and coherence spectra

Both Comptonization and reflection models for the soft X-ray excess can give comparably good fits to both the time-averaged and HF covariance spectra. Both models also require that there is an additional soft component, which we can interpret as direct disc emission, emerging at the softest energies.

We can also use spectral coherence and time lags to constrain the X-ray spectral mechanisms (e.g. McHardy et al. 2004; Fabian et al. 2009). However, the low count rate of RXJ1140 and the relatively short continuously sampled light-curve segments (<11 ks, see Section 3) mean that the statistics are limited. We calculate these following Nowak et al. (1999), using only Obs-1 and 3 (since Obs-2 has a significantly different spectrum and variability). We choose a low- and high-energy band, with 0.3–0.7 and 1.8–2.5 keV, respectively, to best distinguish the different spectral components whilst still containing enough counts.

Fig. 6a shows that there is a soft reverberation lag of ∼200 s seen between the 0.3–0.7 and 1.8–2.5 keV light curves at a frequency of ∼2 × 10^{-3} Hz. But the zero spectral coherence and the dominance of Poisson noise at this frequency means that this lag could be spurious. There is however a clear positive lag at the lowest frequencies (below 2 × 10^{-4} Hz), where the soft leads the harder band. This lag is supported by the good spectral coherence between these bands up to 6 × 10^{-4} Hz (Fig. 6c and d). We note that Poisson noise will not be an issue over such long time-scales. Fig. 6b shows the energy spectrum of this long time-scale soft lead, showing that there is a clear break between the time lags at low and high energy, although the statistics are poor at hard X-ray energies. This feature is not easily compatible with the reflection model shown in Fig. 5b, where a single component dominates the spectrum from 0.4 to 10 keV.

Thus, while the low signal to noise is a problem, these data provide marginal evidence, in terms of spectral coherence and time lag, to support a model in which the bulk of the soft X-ray excess does not have a significantly different spectrum and variability. However, the low count rate of RXJ1140 and the relatively short continuously sampled light-curve segments (<11 ks, see Section 3) mean that the statistics are limited. We calculate these following Nowak et al. (1999), using only Obs-1 and 3 (since Obs-2 has a significantly different spectrum and variability). We choose a low- and high-energy band, with 0.3–0.7 and 1.8–2.5 keV, respectively, to best distinguish the different spectral components whilst still containing enough counts.

Table 1. The xspec model and the best-fitting parameters in Fig. 5. The upper and lower limits are the 90 per cent confidence range.

| Model name | Model expression in xspec v12.8.2 |
|------------|----------------------------------|
| Comptonization | CONSTANT*WABS*ZWABS*(DISKBB+ NTHCOMP + COMPTT + KDBLUR*PEXMON) |

| Spectrum | Component | Parameter | Value |
|----------|-----------|-----------|-------|
| Mean Spec ZWABS | N_{H} (10^{22} cm^{-2}) | 0.0 ± 0.2 | 0.027 ± 0.015 |
| DISKBB | T_{e} (keV) | 0.11 fixed | 0.11 fixed |
| DISKBB | Norm | 135 ± 59 | 135 fixed |
| NTHCOMP | Γ | 2.26 ± 0.11 | 2.26 ± 0.11 |
| NTHCOMP | kT_{e} (keV) | 100 fixed | 100 fixed |
| NTHCOMP | Norm | (1.26 ± 0.10) × 10^{-4} | (8.11 ± 0.57) × 10^{-5} |
| COMPTT | kT_{e} (keV) | 0.38 ± 0.12 | 0.21 ± 0.14 |
| COMPTT | T_{e} (keV) | 10.9 ± 5.8 | 19.3 ± 17.2 |
| COMPTT | Norm | (2.68 ± 0.10) × 10^{-3} | (1.81 ± 0.10) × 10^{-3} |
| KDBLUR | R_{in} (R_{g}) | 20 fixed | 20 fixed |
| PEXMON | Rel_{refl} | -1.0 pegged | -1.0 pegged |
| NTHCOMP | Norm | (5.86 ± 1.10) × 10^{-5} | (2.12 ± 1.67) × 10^{-5} |
| COMPTT | Norm | (1.45 ± 0.14) × 10^{-4} | (9.74 ± 9.74) × 10^{-4} |
| χ^2 | 298/314 | 0.95 | 176/224 = 0.78 |

| Reflection Spectrum | Component | Parameter | Value |
|---------------------|-----------|-----------|-------|
| Mean Spec ZWABS | N_{H} (10^{22} cm^{-2}) | 0.0 ± 0.2 | 0.006 ± 0.005 |
| DISKBB | T_{e} (keV) | 0.11 fixed | 0.11 fixed |
| DISKBB | Norm | 211 ± 38 | 83 ± 17 × 10^{-4} |
| NTHCOMP | Γ | 2.42 ± 0.11 | 2.22 ± 0.10 |
| NTHCOMP | Norm | 5.72 ± 0.00 × 10^{-5} | 3.60 ± 0.00 × 10^{-5} |
| KDBLUR | Index | 5 fixed | 5 fixed |
| KDBLUR | R_{in} (R_{g}) | 4.98 ± 0.13 | 3.05 ± 1.30 |
| RXCONV | Rel_{refl} | -2.19 ± 1.14 | -2.29 ± 1.61 |
| RXCONV | Fe_{pot} | 1.39 ± 0.51 | 0.81 ± 0.84 |
| RXCONV | log ξ | 3.37 ± 0.22 | 2.86 ± 0.45 |
| Cov. Spec NTHCOMP | Norm | 4.90 ± 0.35 × 10^{-5} | 1.08 ± 0.17 × 10^{-5} |
| RXCONV | Rel_{refl} | -0.28 ± 0.14 | -2.60 ± 2.40 |
| RXCONV | χ^2 | 295/312 = 0.95 | 170/222 = 0.77 |
not contribute to emission over the 2–10 keV bandpass, so favouring the low-temperature Comptonization origin over the reflection dominated model.

5 BROAD-BAND SED

5.1 Multiwavelength Data

As outlined in the introduction, RX1140 was reported as an IMBH, whose mass is estimated to be 5–10 \( \times 10^5 \) M\(_\odot\) accreting at a high fraction of the Eddington limit. We construct a multiband SED based on non-simultaneous observations (Fig. 7). We use the XMM–Newton PN spectrum from Obs-1 taken in 2005, together with archival data from the ROSAT PSPCB (1992-06-16) which we reduced using XSELECT v2.4b. The spectra were regrouped fixing a minimum of 25 counts per bin, and are in good agreement with the time-averaged PN XMM–Newton spectrum.

In the optical and UV band, there are simultaneous photometric points from XMM–Newton OM for Obs-1 (UVM2 and UVW1 filters) and Obs-2 and Obs-3 (UVW1, U and B filters). The UVW1 filter fluxes of Obs-1 and Obs-3 are very similar, so are their X-ray fluxes, so we use all OM data from these two observations (except for UVW1 since its waveband is already covered by the combination of UVM2, U and B filter bands). We do not use Obs-2 because it is clearly different in the optical/UV as well as X-ray, with only 90 per cent flux in UVW1, 84 per cent in U and 99 per cent in B compared to Obs-3. These are less suppressed than the X-ray flux (Obs2/Obs3 = 46 per cent in 0.3–2 keV, 63 per cent in 2–10 keV),
indicating that the amplitude of UV/optical variability is less than that of the X-ray over variability time-scales of weeks and years.

Other data points in Fig. 7 include GALEX photometry (obs-date: 2007-03-22), SDSS ugriz PSF photometry and fibre spectrum (obs-date: 2001-03-26), UKIDSS Petrosian magnitude of JYHK photometry (obs-date: 2008-04-21). The difference in the normalization, especially that between the UKIDSS, SDSS fibre fluxes and UGRIZ points, is most likely due to different aperture sizes. We only show the SDSS fibre spectrum for completeness, and do not include these data in the broad-band SED fitting.

5.2 Broad-band SED fitting

We use \texttt{optxagnf} in \texttt{xspec} v12.8.2, to fit the SED from the optical to hard X-ray energies (D12). This includes both intrinsic disc emission and low- and high-temperature Comptonization, as favoured by the spectral fits in Section 4. An additional neutral reflection (\texttt{ckdblur\_pexmon} model, Laor 1991, recoded as a convolution model by Nandra et al. 2007) is added to fit the marginally rising shape above 4 keV. We fix the inclination of the reflector at 30°, and fix the spectral index of the hard Comptonization component around 2.26 (see Section 4). We correct for extinction by a Galactic column and fix the spectral index of the hard Comptonization component at 1.7 (Kalberla et al. 2005). We also allow for intrinsic extinction in the host galaxy. This gives a best fit around $N_\odot = 2 \times 10^{21} \text{ cm}^{-2}$ at $z = 0.0811$ (\texttt{zweabs} model, Morrison & McCammon 1983). Both Galactic and intrinsic reddening are assumed to follow the standard dust-to-gas conversion formula $E(B-V) = 1.7 \times 10^{-22} N_\odot$ (Bessell 1991) and modelled by the \texttt{zredden} and \texttt{zredden} model (Cardelli, Clayton & Mathis 1989) in \texttt{xspec}.

The far-UV GALEX points lie well on the expected disc spectrum from \texttt{optxagnf}, but the optical and near UV points display a curvature similar to that from host galaxy emission. The SDSS images show that the host galaxy of RX1140 is of an Sc type galaxy. Therefore, we select an Sc galaxy template from the SWIRE library (Polletta et al. 2007) and incorporate this into our \texttt{xspec} model. A normalizing constant is added to account for the different star formation rate and stellar mass of the template galaxy, and the host galaxy of RX1140. An additional normalization offset is allowed between the \texttt{UKIDSS} and SDSS ugriz photometric points due to their different aperture sizes sampling different amounts of the host galaxy. Both these normalization factors are well constrained by the data. The shape of \texttt{UKIDSS} JYHK points match well to both the template and the SDSS ugriz points after a scaling of 76 per cent.

Fig. 7 shows the extinction/reddening/aperture corrected data (coloured points, compared to the observed data points in grey) and the best-fitting SED model. The fit statistic is not good (reduced $\chi^2 = 982/330$), but this is mainly due to the small error bars of the photometric points in the optical/UV band.

However, the best-fitting BH mass is $9.6 \times 10^6 M_\odot$. This is almost an order of magnitude higher than the BH mass estimated from optical spectroscopy and reverberation (Greene et al. 2008; Rafter et al. 2011). Using this higher BH mass, the Eddington ratio is correspondingly low, $L/L_{\text{Edd}} = 0.17$, which is in conflict with the classification of this object as an NLS1. But the NLS1 classification is supported by the steep X-ray spectrum, and by the \texttt{optxagnf} coronal radius of $\sim 15 R_g$, consistent with typical values for NLS1 (J12b, D12).

We test how robustly the SED modelling constrains BH mass by fitting pure disc models down to $15 R_g$ (dashed lines) to the UV points for masses of $1.5 \times 10^5$ (blue: $L/L_{\text{Edd}} = 400$), $1.0 \times 10^6 M_\odot$ (orange: $L/L_{\text{Edd}} = 10$) and $1.0 \times 10^7 M_\odot$ (red: $L/L_{\text{Edd}} = 0.17$) as before. The red solid line shows the previous best fit. These disc components all give optical fluxes at 5100 Å which match the observed variable flux (Rafter et al. 2011). However, all the reasonable BH masses overpredict the observed X-ray emission by factors of 10–100 (Fig. 8a). Allowing the disc to extend down to $6 R_g$ for a non-rotating BH, or $1.2 R_g$ for a maximally spinning BH, would make this discrepancy even worse, see Done et al. (2013).

In Fig. 8b, we use the same range of BH masses, but now the aim is to fit the X-ray spectrum, and extrapolate the model to lower energies. The model with a $10^7 M_\odot$ (red curve) can fit the far-UV (and variable optical) data, whereas the model for the $10^5$ and $1.5 \times 10^6 M_\odot$ BH masses underpredict the disc continuum by a factor of 10–50, as the peak of the disc spectrum shifts into the soft X-ray band, and its contribution to the UV and optical emission decreases.

The above tests suggest that the broad-band SED can provide strong constraints to the physical model and relevant parameters, especially the BH mass. We discuss this in more detail in the next section.

6 DISCUSSION

6.1 BH mass estimates

Section 1 summarized previous BH mass estimates for RX1140 from RM technique and $H\beta$ line width. All previous BH masses based on optical spectra report RX1140 to be an IMBH with $M \lesssim 10^6 M_\odot$.

The X-ray variability power spectra also strongly support such a BH low mass, with no observed high-frequency break on timescales longer than 500 s (see Fig. 2). This means that the total excess variance, $\sigma_{\text{rms}}^2$, is high. We include our new data on the $M - \sigma_{\text{rms}}$ relation (Miniutti et al. 2009; Zhou et al. 2010; Ponti et al. 2012). Fig. 9 shows the reverberation mapped subsample of objects from Ponti et al. (2012), where $\sigma_{\text{rms}}$ values were calculated from 40 ks light curves in the 2–10 keV band. For RX1140, $\sigma_{\text{rms}} = 0.11 \pm 0.04$ in Obs-1 and 0.12 $\pm 0.08$ in Obs-2. Obs-3 gives similar $\sigma_{\text{rms}}$ as Obs-1 but with bigger uncertainties due to worse signal to noise. The mass inferred from the linear regression line is $1.25 \times 10^6 M_\odot$. A $10^5 M_\odot$ BH mass lies outside the $\sigma g$ region, but any BH mass within $3 \times 10^{-3} - 3 \times 10^6 M_\odot$ is consistent with the relation (see also Ludlam et al. 2015).

6.2 The SED and mass accretion rate

The BH mass estimate discussed in the previous section highlights the inconsistency between the BH mass derived from the SED models of $\sim 10^7 M_\odot$, and all other determination methods which give $10^6 M_\odot$. For a BH mass of $10^6 M_\odot$, the SED models can either fit the optical/UV flux from the AGN, but then it overpredicts the X-rays (Fig. 8a), or the model can fit the X-rays, but it underpredicts the optical/UV (Fig. 8b). Given that the fraction of optical/UV flux attributed to the AGN is constrained by the observed variability (Rafter et al. 2011), then this requires that the $10^6 M_\odot$ disc fit in Fig. 8a correctly describes the outer disc, with a derived $L/L_{\text{Edd}} = 10$. This estimate is substantially super-Eddington, so there could be substantial energy loss via optically thick advection and/or winds from the inner disc.

In the advection case, part of the energy is swept along with the accretion flow into the BH rather than being emitted as radiation. In the disc wind case, the mass-loss from winds reduces the mass accretion rate in the inner disc, thereby reducing the amount of gravitational energy emitted as radiation. The model used to fit
Figure 8. Broad-band SED fitting is similar as in Fig. 7, but with different BH masses: $M = 9.6 \times 10^6 M_\odot$ (red), $1.0 \times 10^6 M_\odot$ (orange), $1.5 \times 10^5 M_\odot$ (blue). In Panel a, the models primarily fit the UV points and have $L/L_{\text{Edd}} = 0.17$, 10 and 400, respectively, for disc emission outside 15 $R_g$ (see Section 5.2). In Panel b, the models tend to primarily fit the X-ray spectra and have $L/L_{\text{Edd}} = 0.17$, 0.56 and 2, respectively. Solid lines are the total models, while dashed lines are the disc components.

Figure 9. $M-\sigma_{\text{rms}}^2$ relation formed by the RM sample, where $\sigma_{\text{rms}}^2$ is the excess variance of 2–10 keV for 40 ks time-scale. $\sigma_{\text{rms}}^2$ values are taken from Ponti et al. (2012), the RM masses are taken from Peterson et al. (2004, 2005), Denney et al. (2006) and Du et al. (2014). The black solid line is the regression line assuming $\sigma_{\text{rms}}^2$ as an independent variable. Dashed and dotted lines show the $\pm 1\sigma$ and $\pm 2\sigma$ confidence ranges for the new observations. The red vertical line indicates the mean $\sigma_{\text{rms}}^2$ for RX1140, with $\pm 1\sigma$ intervals determined from Obs-1 (orange) and Obs-2 (yellow). The horizontal red line indicates the BH mass of RX1140 predicted by the regression line.

the SED assumes that the situation is sub-Eddington, and therefore that neither of these two processes is important. It follows that this conclusion may no longer be valid for super-Eddington objects, such as may be the case for RX1140 (orange and blue lines in Fig. 8a).

The degree of energy losses due to winds/advection can be estimated from the best-fitting SED model. The parameters of $M = 10^7 M_\odot$, $L/L_{\text{Edd}} = 0.17$ give $L_{\text{hot}} \sim 2 \times 10^{46}$ ergs cm$^{-2}$ s$^{-1}$, which is close to the Eddington limit for the most probable BH mass of $10^6 M_\odot$. This is in support of the proposal of Wang et al. (2014) that super-Eddington BHs have a total luminosity which saturates around the Eddington limit.

However, RX1140 has another unusual feature. It exhibits strong optical variability, as seen in the RM campaign of Rafter et al. (2011). The majority of NLS1 show less optical variability than the broad-line Seyferts (e.g. Ai et al. 2013, but see Kelly et al. 2013). This is somewhat surprising in view of their higher X-ray variability (e.g. Ponti et al. 2012). The unusually strong optical variability in RX1140 could indicate that some of the X-rays are reprocessed within a large scale wind. If so the models above in Fig. 8a, which require only disc emission to fit the optical, may be overestimating the mass accretion rate. None the less, there must still be sufficient X-ray emission to power an additional optical component. The X-ray model fit based on $10^6 M_\odot$ shown in Fig. 8 b has an X-ray peak which has similar $\nu L_\nu$ to that required to explain the far-UV emission. So this model with $L/L_{\text{Edd}} = 0.56$ would require that almost all the X-rays are reprocessed. A more likely reprocessing fraction of 10–50 per cent would require a higher Eddington ratio of 1–5. So perhaps the most plausible model is a combination of the two $10^6 M_\odot$ models in Fig. 8 a and b, where the X-ray emission is partly suppressed by wind/advection energy losses, and the optical emission is correspondingly enhanced by reprocessing in the wind.

6.3 Super-Eddington accretion flow

We note that if winds and advection do play a significant role, it is curious that the X-ray spectrum and variability properties, including the lack of absorption signatures in the X-ray spectra, are not more noticeably different from the other well-studied NLS1s, such as PG 1244+026, RE J1034+396 and RX J0136.9–3510 (e.g. Jin et al. 2009, 2013, Middleton et al. 2009). This raises the possibility that these sources are likewise super-Eddington. PG 1244+026 has an SED which is acceptably well fitted by a $10^7 M_\odot$ BH accreting at about $L_{\text{Edd}}$ (Done et al. 2013). This SED has a distinct outer disc spectral shape in the optical/UV (e.g. Done et al. 2013), which constrains $(M M)^{2/3} \propto (M^2 L/L_{\text{Edd}})^{2/3}$. Reducing the BH mass by
a factor of 4 to $2.5 \times 10^6 \, M_\odot$ i.e. removing the Marconi et al. (2008) radiation pressure correction to the H β line velocity width, then requires $L/L_{\text{Edd}} \sim 16$, i.e. very super-Eddington (see Done & Jin 2015), which would then invalidate the BH spin determination described in Done et al. (2013).

If the majority of all NLS1s are super-Eddington, but the typical broad-line Seyfert 1’s have $L/L_{\text{Edd}} \sim 0.05–0.2$, then this implies a distinct bimodal (or a very long tail), mass accretion rate distribution. Also, such high-energy losses due to advection/winds are probably not seen in the majority of ultraluminous X-ray sources (e.g. Sutton et al. 2015), although they may be present in the more extreme sources discussed by Gladstone, Roberts & Done (2009).

The current data suggest that most of these sources represent moderately super-Eddington flows on to stellar mass BHs with masses of around $30 \, M_\odot$ compared with those with $\sim 10 \, M_\odot$ seen in our Galaxy, due to their lower metallicity resulting in less mass-loss from winds: Zampieri & Roberts (2009). Theoretical models predict rather high efficiency for these flows (Jiang, Stone & Davis 2014, but see also Sądowski et al. 2015 who report lower efficiency). Clearly there remain many aspects of super-Eddington accretion flows which are not yet understood.

7 SUMMARY

In this paper, we use new XMM–Newton data from one of the lowest mass AGN known as a means to better understand the nature of the soft X-ray excess, and how this relates to its broad-band SED. Clearly there remain many aspects of super-Eddington accretion flows which are not yet understood.

We fit the time-averaged X-ray data together with the covariance spectra of the fast variability, and show that both low-temperature Comptonization and highly smeared, ionized reflection models can fit the data, but that both require an additional component at the lowest X-ray energies which we interpret as arising from the inner disc. However, the RMS, lag and coherence spectra all suggest a break in variability properties between the soft and hard X-ray bands, which is not consistent with the reflection model. Instead, these characteristics support the low-temperature Comptonization model as this component does not extend into the 2–10 keV band.

All these properties are similar to other ‘typical’ NLS1s such as PG 1244+026 (Jin et al. 2013), RE J1934+26 (Jin et al. 2009). These characteristics support the low-temperature Comptonization and highly smeared, ionized reflection models.

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