The Seyfert AGN RX J0136.9–3510 and the spectral state of super Eddington accretion flows

Chichuan Jin,* Chris Done, Martin Ward, Marek Gierliński and James Mullaney

Department of Physics, University of Durham, South Road, Durham DH1 3LE

Accepted 2009 June 11. Received 2009 June 5; in original form 2009 March 26

ABSTRACT
We have carried out a survey of long 50 ks XMM–Newton observations of a sample of bright, variable active galactic nuclei (AGN). We found a distinctive energy dependence of the variability in RX J0136.9–3510 where the fractional variability increases from 0.3 to 2 keV, and then remains constant. This is in sharp contrast to other AGN where the X-ray variability is either flat or falling with energy, sometimes with a peak at ~2 keV superimposed on the overall trend. Intriguingly, these unusual characteristics of the variability are shared by one other AGN, namely RE J1034+396, which is so far unique showing a significant X-ray quasi-periodic oscillation (QPO). In addition, the broad-band spectrum of RX J0136.9–3510 is also remarkably similar to that of RE J1034+396, being dominated by a huge soft excess in the Extreme-UV (EUV) to soft X-ray bandpass. The bolometric luminosity of RX J0136.9–3510 gives an Eddington ratio of about 2.7 for a black hole mass (from the H beta line width) of 7.9 × 10^7 M⊙. This mass is about a factor of 50 higher than that of RE J1034+396, making any QPO undetectable in this length of observation. None the less, its X-ray spectral and variability similarities suggest that RE J1034+396 is simply the closest representative of a new class of AGN spectra, representing the most extreme mass accretion rates.

Key words: accretion, accretion discs – galaxies: active – galaxies: individual: RX J0136.9-3510 – galaxies: nuclei – galaxies: Seyfert – X-rays: galaxies.

1 INTRODUCTION

Active galactic nuclei (AGN) are powered by gas accreting on to the central super-massive black hole. As such their intrinsic spectra are determined simply by the mass and spin of the black hole, together with the mass accretion rate, although their observational appearance is also affected by absorption. The discovery that the black hole mass scales with the host galaxy bulge properties (Magorrian et al. 1998; Gebhardt et al. 2000) presented a means to classify the bewildering variety of unabsorbed AGN spectra in terms of two of these three intrinsic properties. It was found that different optical spectral types clearly correlated with black hole mass and mass accretion rate, with the narrow-line Seyfert 1 galaxies (NLS1s; defined as Hβ emission-line FWHMs less than 2000 km s^-1 and [O iii]/Hβ line ratios less than 3.0, Goodrich 1989) as examples of lower mass black holes accreting at higher Eddington ratio than the typical broad-line Seyfert 1s (BLS1s), which in turn had higher Eddington ratio/lower black hole masses than the LINERs (e.g. Osterbrock & Pagge 1985; Boller, Brandt & Fink 1996; Mathur 2000; Boroson 2002; Bian et al. 2008; Winter et al. 2009).

NLS1s are intrinsically very luminous in the EUV/soft X-ray bandpass, comprising over half the AGN found in the softest X-ray selected surveys (Puchnarewicz et al. 1992; Grupe 1996; Edelson et al. 1999). This strong ionizing flux results in intense permitted optical Fe II emission lines from the broad-line region and high-ionization species often referred to as coronal lines (Wills et al. 1999; Kuraszkiewicz et al. 2000; Ghosh et al. 2004; Mullaney & Ward 2008). Other observed characteristics include rapid X-ray variability (Boller et al. 1996; Leighly 1999a) and steeper soft X-ray spectra than those of BLS1s (Brandt, Mathur & Elvis 1997; Leighly 1999b). Taken together these distinctive properties have led to them being considered as the scaled up counterparts of the most luminous accretion states seen in stellar mass black hole binary (BHB) systems, i.e. those having ‘high’ and ‘very high’ states (Pounds, Done & Osborne 1995; Middleton, Done & Gierliński 2007).

This link with the stellar mass black hole systems was strengthened by the first detection of an X-ray quasi-periodic oscillation (QPO) in the NLS1 RE J1034+396 (Gierliński et al. 2008) as QPOs are commonly seen in the BHB (high-frequency QPO, low-frequency QPO, plus some others seen only in GRS1915+105: e.g. Morgan, Remillard & Greiner 1997; Remillard & McClintock 2006), they are all generally most prominent in the ‘very high state’. Simple scaling from BHB then predicts that QPOs should be common amongst NLS1 as a class due to their high-mass accretion rate. None the less,
RE J1034+396 is extreme even amongst NLS1 (see below), and it may be that its so far unique QPO detection is due more to its unusual properties than to any simple scaling from the known QPOs in BHB.

We first summarize the properties of RE J1034+396, in order to provide the context for our study of RX J0136.9−3510, which is reported in this paper. The most obvious unusual feature of RE J1034+396 is its broad-band spectral energy distribution (SED). This exhibits a peak in the far ultraviolet (UV) which connects smoothly on to the steep soft X-ray spectrum. These components form a huge ‘soft X-ray excess’ with respect to the $T ≈ 2.2$ X-ray tail which dominates above $\sim 2$ keV (Puchnarewicz et al. 1995; Casebeer, Leighly & Baron 2006; Middleton, Done & Gierliński 2007; Middleton et al. 2009). The energy dependence of this variability is also very different to that commonly seen in other AGN. The fractional variability amplitude (as measured by rms) rises steeply to $\sim 2$ keV and then levels off. This is most likely due to the presence of two separate components in the X-ray spectrum, with the variability being associated with the X-ray tail, whilst the soft excess component remains more or less constant (Middleton et al. 2009). This situation contrasts with the flat or falling rms spectra seen in other AGN, sometimes with a peak at $\sim 2$ keV superimposed on this (Vaughan et al. 2003; Vaughan & Fabian 2004; Fabian et al. 2004; Gierliński & Done 2006; Ponti et al. 2006; Petrucci et al. 2007; Larsson et al. 2008), which makes it more likely that the apparent soft excess in these objects is due instead to a single spectral component distorted by reflection and/or absorption (Crummy et al. 2006; Gierliński & Done 2006).

In this paper, we make use of the unusual energy dependence of the X-ray variability in RE J1034+396 to search for potentially similar objects. A survey of all long ($\geq 50$ ks) XMM–Newton observations of bright and variable AGN yielded a similar rms shape only in one object RX J0136.9−3510 (2MASSI J0136544−350952). This AGN also has a similar broad-band spectrum to RE J1034+396, suggesting that they may form a subclass of the highest mass accretion rate AGN.

2 SOURCE SELECTION

We searched the XMM–Newton Master Log & Public Archive for pointed observations with exposure times in the PN instrument of $\geq 50 000$ s in ‘subject category’ ‘AGN, QSOs, BL-Lacs and X-ray binary’. This resulted in 115 observations available at the time of our study (2008 November). We further refined this criteria to include only those objects with PN count rates of $\geq 1.0$ counts s$^{-1}$ to include only bright sources for which the variability can be well determined.

We also searched the XMM–Newton Serendipitous Source Catalogue (2XMMi Version) for serendipitous bright AGN detected in similarly long exposures, by setting PN_8_flux $\geq 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ and PN_on_time $\geq 50 000$ s. This yielded 29 observations. We then combined these two samples to give a total of 68 individual sources. For each data set, we calculated the fractional variability amplitude using LCSTATS in XRONOS 5.21. This is defined as the rms of the intrinsic (corrected for error bars) variance about the light curve mean, $\sigma^2$, normalized to this mean, $I$. Only sources which are strongly and significantly variable can provide constraints on the energy dependence of the variability, so we select only sources for which the rms is $\geq 0.1$ at more than 3 sigma significance determined from the uncertainty on the rms, which relates to the $\chi^2$ distribution as the variance is a sum of squares, (see e.g. Done et al. 1990). This filtering leaves 19 AGNs.

We then excluded 2 known BL-Lac objects (PKS2155−304 and 0716+714) since their X-ray variability is thought to be due to jet related processes. For the two observations of NGC 4051, one (0157560101) only has an exposure time of 49 917 s, while the other (0109141401) does not have the PN_time value in the catalogue, so they were formerly excluded by the filtering. However, since NGC 4051 is a well-known, bright, NLS1 and our study is not a statistical study, we still included these two observations. This inclusion should not affect our general conclusions. We also included the famous Seyfert 2 AGN, MCG-5-23-16 (0302850201), although its rms variability is only 0.073. This gives us a total of 19 AGNs for subsequent study, with one or more selected observations for each of them.

For each of these data sets, we calculated the fractional variability amplitude as a function of energy using the method of Gierliński & Done (2006). This showed the standard range of rms spectral shapes. Only RX J0136.9−3510 (0303340101) displayed the very different type of rms spectrum associated with the QPO AGN, RE J1034+396, in which the fractional amplitude rises as a function of energy, then remains high. Having identified this unusual AGN, we investigate its properties in more detail below.

3 RX J0136.9−3510: LIGHT CURVE AND RMS SPECTRUM

The light curve and rms spectrum are extracted from the X-ray data (0.3−10 keV), using SAS7.1.0 and XRONOS 5.21. We use regions with radius of 16, 9.2 and 8.6 arcsec for PN, MOS1 and MOS2, respectively. No significant pile-up is seen from the SAS command EPATPLOT so no central region was excluded. There are high background flares during the first 10 000 s, so we exclude these data, resulting in $\sim 40 000$ s (with background count rate $\sim 0.4$ counts s$^{-1}$) for the rms spectrum generation. Fig. 1 shows the resultant total light curve (PN, MOS1 and MOS2), binned on 200 s. The source shows strong variability (also seen by Ghosh et al. in preparation), with the rms fractional variation being 0.13. However, there is no obvious QPO, and a power spectral analysis shows no peaks above even 1$\sigma$ significance using the method of Vaughan (2005).

Figure 1. Background subtracted light curve of RX J0136.9−3510 binned on 200 s. The exposure start time (UTC) is 2005-12-14 20:45:30, but the first 10 ks was excluded due to the high background contamination.
The optical spectrum has an Fe II/Hβ emission-line fitting. The data is from D. Grupe, and we show this figure with his permission.

Figure 3.

The rms spectrum has an Fe II/Hβ flux ratio of ~8.3 (Grupe et al. 1999), compared to the ~1 average for NLS1s (Véron-Cetty, Véron & Goncalves 2001), making RX J0146.9−3510 an unusual NLS1 (Ghosh et al. 2004). We use the optical spectrum shown in Fig. 3 (D. Grupe, private communication) to estimate the black hole mass.

We rebin the light curve on 2000 s in order to provide enough count statistics to calculate the fractional variability as a function of energy. Fig. 2 shows that this rms rises steeply from 0.3 to ~2 keV, then flattens off. The weak decrease from 2–10 keV is not significant as the low count rate means there are large uncertainties on the last point. We also calculated the rms spectra from count statistics to calculate the fractional variability as a function of energy. Fig. 2 shows that this rms rises steeply from 0.3 to ~7 keV, then flattens off. The weak decrease from 2–10 keV is not significant as the low count rate means there are large uncertainties on the last point. We also calculated the rms spectra from 200 s binning, but this is not significantly different.

4 BLACK HOLE MASS ESTIMATION

The optical spectrum has an Fe II/Hβ flux ratio of ~8.3 (Grupe et al. 1999), compared to the ~1 average for NLS1s (Véron-Cetty, Véron & Goncalves 2001), making RX J0146.9−3510 an unusual NLS1 (Ghosh et al. 2004). We use the optical spectrum shown in Fig. 3 (D. Grupe, private communication) to estimate the black hole mass.

The Hβ line width is used as a proxy for this (see Woo & Urry 2002, and references therein) from

\[ M_{BH} = 4.817 \times \left( \frac{\lambda L_{\lambda}(5100\text{Å})}{10^{44} \text{erg s}^{-1}} \right)^{0.7} \text{FWHM}^2. \]  

Comparing this method for a sample of AGN with reverberation mapping, the rms difference is about 0.5 dex (Woo & Urry 2002). The flux at λ = 5100 Å from the optical spectrum is \( \sim 1.5 \times 10^{-16} \text{erg cm}^{-2} \text{s}^{-1} \). The luminosity distance is \( D_L = 1455.2 \text{Mpc} \) for \( z = 0.289 \) assuming \( H_0 = 72 \text{km Mpc}^{-1} \), \( \Omega_M = 0.27 \), and \( \Omega_{\Lambda} = 0.73 \).

Estimating the FWHM of the line is not straightforward as the Hβ line profile is complex. There is clearly also a component from the extended narrow-line region (NLR). This should be similar to the profile of the [O iii] emission line. So, Grupe et al. (1999) use a template constructed from the [O iii]5007 line to represent the narrow component, together with a broader Gaussian component, with FWHM = 1320 km s\(^{-1}\), to reconstruct the Hβ line. This gives a black hole mass estimate of \( 1.3 \times 10^7 \text{M}_\odot \).

However, the optical spectrum plainly has limited signal-to-noise ratio, and the [O iii] 5007 line is probably contaminated by Fe II emission as it should be in 3:1 ratio with the (unobserved) [O iii] line at 4959 Å. Hence, we perform our own best fit of the Hβ line profile with a Gaussian of width 870 km s\(^{-1}\) for the narrow-line component, see Fig. 3. This gives a FWHM for the broad component of 3200 ± 2600 km s\(^{-1}\), with a (not significant) blueshift of \(-370 \pm 1100 \text{km s}^{-1}\). Using our new value for the FWHM, the resultant black hole mass is 7.85 × 10^7 M\(_\odot\).

Even with this lower black hole mass, this AGN is still probably ~10× more massive than the QPO AGN, RE J1034+396 (with the previous mass estimate being ~50× larger). Thus, any similar QPO in RX J0136.9−3510 would be on time-scales 10–50× larger, requiring a much longer X-ray observation in order to detect it.

5 BROAD-BAND SED ANALYSIS AND EDDINGTON RATIO

We use the standard products to obtain the XMM–Newton X-ray (PN) spectra and optical/UV (OM) photometry. We then combine these with selected continuum points from the (non-simultaneous) optical spectrum (D. Grupe, private communication) using FLX2XSP to incorporate these into the same format as the XMM–Newton data. We likewise include the J, H and K near-infrared (near-IR) flux points from Two Micron All Sky Survey (2MASS), and perform all spectral fitting using XSPEC11.3.2.

We follow the approach of Vasudevan & Fabian (2009) in modelling the broad-band SED, using DISKPN to model an accretion disc extending down to the last stable orbit around a non-spinning black hole. However, our source is at \( z = 0.289 \), so we modify the DISKPN code to incorporate the redshift dependence. The normalization of the DISKPN model is \( (M^2 \cos i)/(D_{\text{dpc}}^2 \beta^4) \) where \( M \) is the mass in solar units, \( D_{\text{dpc}} \) is the distance in kpc and the cosine of the inclination and colour temperature correction (\( \cos i \) and \( \beta \), respectively) are both set to unity following Vasudevan & Fabian (2009). We start at the highest estimated black hole mass in Section 4, which gives a DISKPN normalization of 2910, and fix this in the spectral fitting. Compton scattering of these disc photons can be approximated by a broken power law (BKPPOWER), with index of \( \Gamma = 0.33 \) below a break at 3\( kT_{\text{disc}} \). We then added a low temperature Comptonization component to model the soft excess, using COMPTT, with seed photons set to the disc temperature. We assume that these intrinsic
components are absorbed by both gas and dust in our Galaxy, and so fix this parameter to the Galactic HI column\(^1\) (\(N_{\text{H}}\)) value of \(N_{\text{H}} = 0.0628\) \(\times 10^{22}\) \(\text{cm}^{-2}\). The reddening (\(\text{redden}\)) is linked to this assuming a \(E(B-V) = 1.7 \times 10^{-22} N_{\text{H}}\) (Spitzer & Lyman 1978). Since the optical data were not simultaneous with the UV and X-ray data, we allow for long time-scale variation as a constant offset in normalization between the \(\text{XMM–Newton}\) data and the optical spectrum. We exclude the IR data points from our spectral fitting, since the model we use describes the intrinsic emission from the accretion flow whereas the IR emission is likely due to reprocessing by dust in the host galaxy, plus a possible contribution from intrinsic starlight. The resultant best-fitting parameters are given in Table 1.

Fig. 4 shows the rebinned data (black), with the optical flux corrected for their best-fitting normalization of \(\sim 0.92\times\) that of the \(\text{XMM–Newton}\) UV and X-ray spectra, and all data points are corrected for absorption/reddening. This model is a good description of the overall shape of the optical/UV/X-ray spectrum and gives a bolometric flux of \(8.8 \times 10^{-11}\) \(\text{ergs} \cdot \text{s}^{-1} \cdot \text{cm}^{-2}\), corresponding to a bolometric luminosity of \(31\) \(\text{eV}\). The UV region is then dominated by disc emission, though the Comptonization still is 80, and the resultant disc temperature rises to 31 \(\text{eV}\). The Comptonization still is 80, and the resultant disc temperature rises to 31 \(\text{eV}\).

The Seyfert AGN RX J0136.9—3510 and the spectral state of super Eddington accretion flows

| constant | \(T_{\text{disc}}\) (keV) | \(kT_e\) (keV) | \(\tau\) | \(N_{\text{comp}}\) | \(\Gamma_{\text{pow}}\) | \(N_{\text{pow}}\) | \(\chi^2/d.o.f\) |
|----------|-----------------|-------------|-----|-------------|-----------|------------|--------------|
| 0.92 \(\pm 0.10\) | 7.93 \(\pm 0.28\) | 0.28 \(\pm 0.03\) | 12.17 \(\pm 0.72\) | 10.64 \(\pm 2.37\) | 0.73 | 2.28 \(\pm 0.07\) | 1.12 \(\pm 0.55\) | 475/493 |

\(\chi^2/d.o.f\) for RX J0136.9—3510 is as high as \(13!\) This is the highest known Eddington ratio for an AGN (Shen et al. 2008; Vasudevan & Fabian 2009). Thus, modelling the SED with the two extreme mass estimates gives a range for the Eddington ratio of RX J0136.9—3510 of 2.7—13.2. Even without models, simply integrating the observed spectrum using a straight line to connect the UV and soft X-ray data gives an Eddington ratio of \(\sim 1\) for the highest black hole mass, making this a robustly super-Eddington source.

6 SUMMARY AND CONCLUSION

In this paper, we report that RX J0136.9—3510 is the only well observed, X-ray bright, variable AGN which has a similar energy dependence to its X-ray variability as the so far unique QPO AGN, RE J1034.3+396. Its Eddington ratio is similarly high, around 3, although its larger mass means any QPO is undetectable in our data. Its broad-band SED is also remarkably similar to that of RE J1034.3+396, being well modelled by a low temperature, optically thick Comptonization of the accretion disc spectrum, plus a tail extending to higher energies. Spectra such as this have also been fit by ‘slim’ disc models (Abramowicz, Kato & Matsumoto 1989), where the accretion rate is so high that radiation cannot easily escape vertically before it is carried radially (advected) along with the flow (Pucharewicz et al. 2001; Wang & Netzer 2003). However, simple slim disc models do not fit the curvature of the soft X-ray spectra as well as Comptonization (Middleton et al. 2009), although more complex models of slim discs do include such scattering in the disc atmosphere (e.g. Kawaguchi 2003).

Low temperature, optically thick Comptonization is also occasionally seen in the stellar mass BHB systems, for example, in the most extreme mass accretion rate spectra of GRS 1915+105 (Middleton et al. 2006, 2009). Recent studies of spectra of the ultraluminous X-ray sources also indicate that these are well modelled by such material (Gladstone, Roberts & Done 2009). This evidence suggests that there is indeed a distinct spectral state which can only be attained by super Eddington flows (Gladstone et al. 2009). Future long duration X-ray observations of AGN should reveal additional examples, and objects with low black hole masses are potential QPO candidates.

ACKNOWLEDGMENTS

We acknowledge D. Grupe for permission to use the optical data. CCJ acknowledges financial support through Durham Doctoral Fellowship.

REFERENCES

Abramowicz M. A., Kato S., Matsumoto R., 1989, PASJ, 41, 1215
Bian W., Hu C., Gu Q., Wang J., 2008, MNRAS, 390, 752
Boller Th., Brandt W. N., Fink H., 1996, A&A, 305, 53

\(^1\) http://heasarc.gsfc.nasa.gov/cgi-bin/Tools/w3nh/w3nh.pl
Boroson T. A., 2002, ApJ, 565, 78
Brandt W. N., Mathur S., Elvis M., 1997, MNRAS, 285, L25
Casebeer D. A., Leighly K. M., Baron E., 2006, ApJ, 637, 157
Crummy J., Fabian A. C., Gallo L., Ross R. R., 2006, ApJ, 365, 1067
Done C., Ward M. J., Fabian A. C., Kunieda H., Tsuruta S., Lawrence A., Smith M. G., Wamsteker W., 1990, MNRAS, 243, 713
Edelson R., Vaughan S., Warwick R., Pucharewicz E., George I., 1999, MNRAS, 307, 91
Fabian A. C., Miniutti G., Gallo L., Boller Th., Tanaka Y., Vaughan S., Ross R. R., 2004, MNRAS, 353, 1071
Gebhardt K. et al., 2000, ApJ, 539, L13
Gierliński M., Done C., 2006, MNRAS, 371, L16
Gierliński M., Middleton M., Ward M., Done C., 2008, Nat, 455, 369
Ghosh K. K., Swartz D. A., Tennant A. F., Wu J., Ramsey B., 2004, ApJ, 607, L111
Gladstone J., Roberts T., Done C., 2009, MNRAS, in press
Goodrich R. W., 1989, ApJ, 342, 224
Grupe D., 1996, PhD thesis, Univ. Göttingen
Grupe D., Beuermann K., Mannheim K., Thomas H. C., 1999, A&A, 350, 805
Kawaguchi T., 2003, ApJ, 593, 69
Kuraszkiewicz J., Wilkes B. J., Czerny B., Mathur S., 2000, ApJ, 542, 692
Larsson J., Miniutti G., Fabian A. C., Miller J. M., Reynolds C. S., Ponti G., 2008, MNRAS, 384, 1316
Leighly K. M., 1999a, ApJS, 125, 297
Leighly K. M., 1999b, ApJS, 125, 317
Magorrian J. et al., 1998, ApJ, 115, 2285
Mathur S., 2000, MNRAS, 314, L17
Middleton M., Done C., Gierliński M., Davis S. W., 2006, MNRAS, 373, 1004
Middleton M., Done C., Gierliński M., 2007, MNRAS, 381, 1426
Middleton M., Done C., Ward M., Gierliński M., Schurch N., 2009, MNRAS, 394, 250
Morgan E. H., Remillard R. A., Greiner J., 1997, ApJ, 482, 993
Mullaney J. R., Ward M. J., 2008, MNRAS, 385, 53
Osterbrock D. E., Pogge R. W., 1985, ApJ, 297, 166
Petrucci P. O. et al., 2007, A&A, 470, 889
Potti G., Miniutti G., Cappi M., Maraschi L., Fabian A. C., Iwasawa K., 2006, MNRAS, 368, 903
Pounds K. A., Done C., Osborne J. P., 1995, MNRAS, 277, L5
Pucharewicz E. M. et al., 1992, MNRAS, 256, 589
Pucharewicz E. M., Mason K. O., Siemiginowska A., Pounds K. A., 1995, MNRAS, 276, 20
Pucharewicz E. M., Mason K. O., Siemiginowska A., Fruscione A., Comastri A., Fiore F., Cagnoni I., 2001, ApJ, 550, 644
Remillard R. A., McClintock J. E., 2006, ARAA, 44, 49
Shen Y., Greene J. E., Strauss M. A., Richards G. T., Schneider D. P., 2008, ApJ, 680, 169
Spitzer L. Jr., 1978, J. Roy. Astron. Soc. Canada, 72, 349
Vasudevan R. V., Fabian A. C., 2009, MNRAS, 392, 1124
Vaughan S., 2005, A&A, 431, 391
Vaughan S., Fabian A. C., 2004, MNRAS, 348, 1415
Vaughan S., Edelson R., Warwick R. S., Uttley P., 2003, MNRAS, 345, 1271
Véron-Cetty M., P., Véron P., Goncalves A. C., 2001, A&A, 372, 730
Wang J.-M., Netzer H., 2003, A&A, 398, 927
Wills B. J., Lair A., Brotherton M. S., Wills D., Wilkes B. J., Ferland G. J., Shang Z., 1999, ApJ, 515, L53
Winter L. M., Mushotzky R. F., Reynolds C. S., Tueller J., 2009, ApJ, 690, 1322
Woo Jong-hak, Urry C. M., 2002, ApJ, 579, 530

This paper has been typeset from a \TeXfile prepared by the author.