THE OPTICAL TO X-RAY SPECTRUM OF THE BROAD-LINE ULTRASOFT AGN RE J2248-511

R. L. C. Starling[1], E. M. Puchnarewicz[1], E. Romero-Colmenero[2] and K. O. Mason[1]

[1]*Mullard Space Science Laboratory, University College London, Holmbury St. Mary, Dorking, Surrey RH5 6NT, UK*

[2]*South African Astronomical Observatory, PO Box 9, Observatory, 7395 South Africa*

ABSTRACT

We present a series of monitoring observations of the ultrasoft broad-line Seyfert galaxy RE J2248-511 with *XMM-Newton* . Previous X-ray observations showed a transition from a very soft state to a harder state five years later. We find that the ultrasoft X-ray excess has re-emerged, yet there is no change in the hard power-law. Reflection models with a reflection fraction of ≥ 15, and Comptonisation models with two components of different temperatures and optical depths (kT$_1$ = 83 keV, T$_1$ = 30 eV, $\tau_1 = 0.8$; kT$_2$ = 3.5 keV, T$_2$ = 60 eV, $\tau_2 = 2.8$) can be fit to the spectrum, but cannot be constrained. The best representation of the spectrum is a model consisting of two blackbodies (kT$_1 = 0.09 \pm 0.01$ keV, kT$_2 = 0.21 \pm 0.03$ keV) plus a power-law ($\Gamma = 1.8 \pm 0.08$). We also present simultaneous optical and infrared data showing that the optical spectral slope also changes dramatically on timescales of years. If the optical to X-ray flux comes primarily from a Comptonised accretion disk we obtain estimates for the black hole mass $\sim 10^8$ M$_\odot$, accretion rate $\sim 0.8 \dot{M}_{Edd}$ and inclination $\cos(i) \geq 0.8$ of the disk.

INTRODUCTION

Studies of *ROSAT* PSPC slopes in AGN have concluded that sources with steep soft X-ray (0.1-2.4 keV) continuum slopes in addition to broad optical emission lines (Hβ FWHM$\geq$3000 km s^{-1}) are simply not found in nature (Boller, Brandt & Fink 1996; Wandel & Boller 1998). The steep soft X-ray slopes characteristic of Narrow-line Seyfert 1 galaxies (NLS1s; whose Hβ FWHM$\leq$2000 km s^{-1}) are thought to be due to a small mass black hole with a high accretion rate (eg Pounds, Done & Osborne 1995) or perhaps due to a broad line region (BLR) which forms relatively far out from the central black hole (Puchnarewicz et al. 1992).

RE J2248-511 is a radio-quiet EUV-selected AGN ($z = 0.101$) discovered by the *ROSAT* Wide Field Camera (Pounds et al. 1993), and classified as a normal broad-line Seyfert 1 galaxy (Mason et al. 1995) with Hβ FWHM$\sim$3000 km s^{-1}. A subsequent observation with the *ROSAT* PSPC (Puchnarewicz et al. 1995) found that the soft X-ray spectrum was very soft and was best-fitted with a broken power law where $\Gamma = 4.13$ at energies below 0.25 keV (and $\Gamma = 2.62$ at higher energies). Thus it differs from a NLS1 in that it has *high* velocity BLR clouds, yet a very steep, ultrasoft X-ray spectrum. This puts it in a category comprising, to our knowledge, only 3 AGN with both these characteristics (RE J2248-511, 1H 0419-577 and RXJ0437.4-4711).

RE J2248-511 was also observed by *ASCA* in 1997 (Breeveld et al. 2001). These observations showed that the soft excess (below 2.0 keV) had completely disappeared and the entire 0.5-10 keV spectrum could be represented by a single power law. Large amplitude variability in the soft X-ray region has also been observed in another of the broad-line ultrasoft AGN 1H 0419-577 (Guainazzi et al. 1998, Turner et al. 1999, Page et al. 2002). This two-state behaviour has led to comparisons with Galactic black holes (GBHs). Page et al. (2001) show that the 0.2-10 keV spectrum of 1H 0419-577 closely resembles that of two Comptonised components, although these cannot be well constrained, and that the variability between *XMM-Newton* and *ASCA* is explained by a change in optical depth of the Comptonising material. Comptonisation has also been proposed as a possible source for the X-ray emission of RE J2248-511 (Breeveld et al. 2001) which we will investigate in this paper.

Here, we present the results of a recent multi-wavelength monitoring campaign consisting of observations from *XMM-Newton* and the South African Astronomical Observatory (SAAO), to examine the long-term variability of this source and the relationship between the X-ray emitting components and the response of the BLR.

XMM-NEWTON OBSERVATIONS

RE J2248-511 was observed by the EPIC (Strüder et al. 2001; Turner et al. 2001) and RGS (den Herder et al. 2001) instruments on-board *XMM-Newton* (Jansen et al. 2001) on 2000 October 26 (17.6 ks pn), 2001 April 21 ($\sim$8.5 ks) and 2001 October 31 (15.4 ks pn). The Optical Monitor was switched off since a nearby bright star saturates the field. All EPIC instruments were in small window mode through the medium filter. About 4.5 ks of the 2001 April observation was contaminated by an extremely high background flare which makes the source difficult to distinguish above the noise. For this reason we do not use these data here. We will concentrate on the EPIC pn data for this analysis since the MOS cameras were in small window free running mode which has not yet been fully calibrated, and the pn data have the higher net count rate.

The raw data from all observations were processed with the *XMM-Newton* SAS (Science Analysis Software) version 5.3. We extracted a circular region around the source with radius 41.3 arcsec. Background subtraction was done using a nearby source-free region 4x larger in radius than the source extraction region. We summed the spectra from the 2000 October and the 2001 October pn observations to increase signal to noise, having first confirmed that no significant variability occurs either during or between the two observations. The latest EPIC pn response file for small window medium filter single events has been used. The resulting spectrum is grouped such that a minimum of 20 counts fall in each bin so χ^2 statistics apply. The mean net count rate is 5.71$\pm$0.02 counts s^{-1}.

X-RAY SPECTRAL ANALYSIS

Spectral analysis was done using the X-ray spectral fitting package XSPEC, using the χ^2 minimization technique. We have restricted the considered energy range to 0.3-10.0 keV as there may be uncertainties in the instrument calibration at energies outside this range. We find that a simple power-law cannot fit the spectrum over this range largely due to the presence of a strong soft X-ray excess (Figure 1).

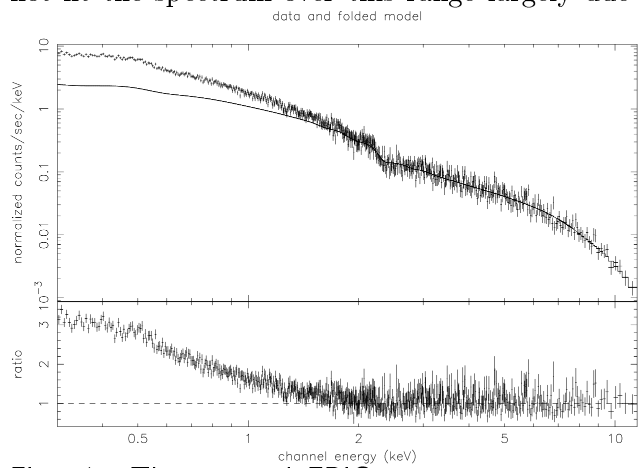

Fig. 1. The summed EPIC pn spectrum is shown against a power-law model with galactic absorption.

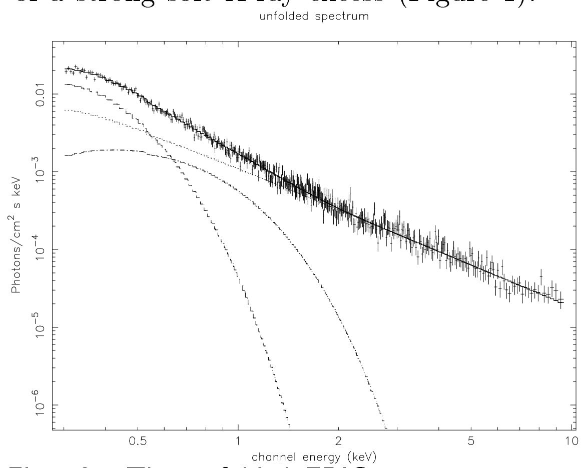

Fig. 2. The unfolded EPIC pn spectrum with the best-fitting model of 2 blackbodies and a power-law plus galactic absorption.

The pn spectrum is well fitted with a model consisting of two blackbodies dominating at low energies with temperatures kT$_1$ = 0.09 ± 0.01 keV and kT$_2$ = 0.21 ± 0.03 keV, plus a power-law with $\Gamma = 1.8\pm0.08$ (χ^2/dof = 458/468; Figure 2). The power-law slope is consistent with the overall 2-10 keV spectrum of Seyferts in general, which have indices typically $\Gamma \sim$1.8-2.0. The X-ray flux in the 0.3-10.0 keV energy range is 9.83$\times$10^{-12} erg cm^{-2} s^{-1}, corresponding to a luminosity of 4.74 $\times$10^{44} erg s^{-1} (assuming H$_0$ = 50.0 and q$_0$ = 0.0). Upper limits on the equivalent widths of an Iron line at 6.4 keV (in the rest frame of the source) are 60 eV for a narrow line ($\sigma = 0.01$) and 50 eV for a broad line ($\sigma = 0.3$). Inclusion of the narrow line gives an improvement according to the F-test of F statistic value = 2.14 and probability = 9.7$\times$10^{-2}.

The Galactic column density was fixed at 1.4×10^{20} cm^{-2} (Puchnarewicz et al. 1995) in all fits. Adding an intrinsic absorption component gives no significant improvement to the fit.

Physical Models

We tried a simple power-law-with-reflection model (Magdziarz & Zdziarski 1995), where incoming photons may be reflected off ionised material such as an accretion disk. This gives a good fit only if the X-ray flux is reflected with a reflection fraction of $\geq$15 and χ^2/dof = 721/659.

Comptonisation has often been suggested as a source of both the soft X-ray and hard X-ray spectrum so we investigated a number of such possibilties using the comptt model within XSPEC (Titarchuk 1994). The best fitting model (χ^2/dof = 672/656; Figure 3) is a hot optically thin component (kT$_1$ = 83 keV, τ_1 = 0.8) irradiated by a 30 eV photon temperature, alongside a cooler optically thick component (kT$_2$ = 3.5 keV, τ_2 = 2.8) irradiated by a 60 eV temperature medium, both upscattering the incident photons. However, while the parameters may appear physically realistic they cannot be reasonably constrained.

We also note that a multi-temperature disk blackbody plus Comptonisation can also fit the spectrum well with χ^2/dof = 713/654, but again the parameters are unconstrained.

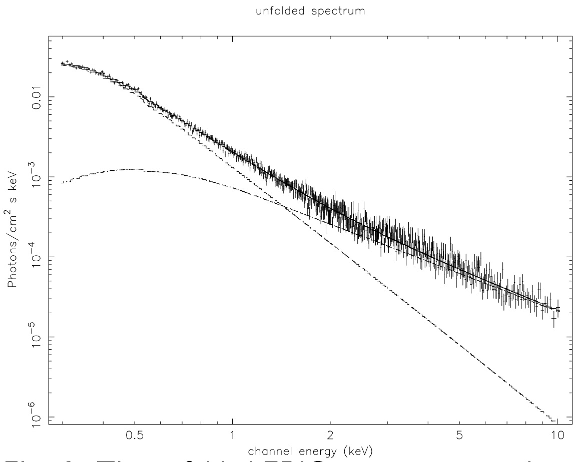

Fig. 3. The unfolded EPIC pn spectrum and double Comptonisation model.

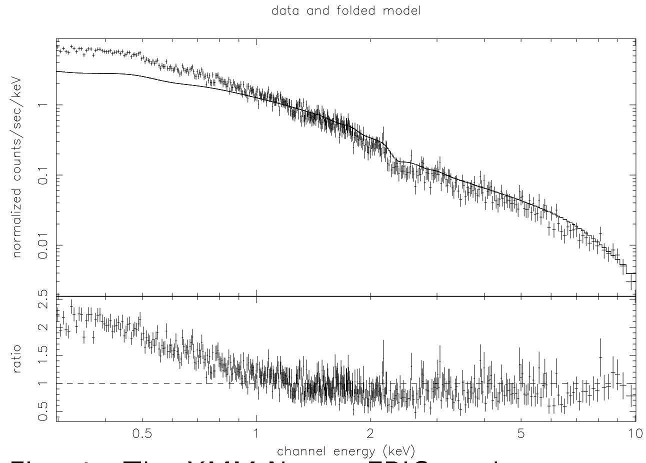

Fig. 4. The *XMM-Newton* EPIC pn data in the 0.7-10 keV range, together with the power-law model which best fits the *ASCA* GIS2 and GIS3 data. The lower panel shows the ratio of the fit to the data, clearly showing excess emission in the pn continuum below 1 keV.

COMPARISON WITH *ASCA* AND *ROSAT*

Comparing the data from all three missions (see also Puchnarewicz et al. 1995 and Breeveld et al. 2001) in the overlapping energy range of 0.7-2.0 keV by simply fitting a power-law (Table 1), we find that in the *XMM-Newton* observations RE J2248-511 is in a much softer state than at the time of the *ASCA* observation (Γ = 2.46 in *XMM-Newton* but 2.05 in *ASCA* ; for *ASCA* , the SIS response is uncertain below 1 keV, so only the GIS data were used). The power-law slope measured with the *ROSAT* PSPC is softer still (Γ = 2.7), although it should be borne in mind that there are reports that the PSPC may over-estimate Γ by as much as 0.4 in which case the *XMM-Newton* and *ROSAT* PSPC data would not be inconsistent. We also note that the error on the PSPC slope is large enough to be consistent with either the *XMM-Newton* or *ASCA* slopes over this range.

Thus, the soft X-ray component first observed with *ROSAT* which subsequently disappeared in the *ASCA* observation (Breeveld et al. 2001), now seems to have re-appeared in *XMM-Newton* (Figure 4). The 2-10 keV spectrum has changed relatively little (in flux and spectral form) between the *ASCA* and *XMM-Newton* observations. From the two-blackbody-plus-power-law fit to the *XMM-Newton* EPIC pn data (kT$_1$ = 0.09 ± 0.01 keV, kT$_2$ = 0.21 ± 0.03 keV, $\Gamma = 1.8 \pm 0.08$), we calculate a flux in the soft component (ie in the two blackbodies; 0.3-2.0 keV) of 2.49×10^{-12} erg cm^{-2} s^{-1}.

Table 1. Power-law fits to the *ROSAT* PSPC, *ASCA* GIS 2 and 3 (fitted simultaneously) and *XMM-Newton* EPIC pn data in the overlapping range of 0.7-2.0 keV; z = 0.101, Galactic absorption = 1.4×10^{20} cm^{-2} (both fixed), no intrinsic absorption.

	Γ	norm ($\times10^{-3}$)	χ^2/dof
ROSAT PSPC (1993)	$2.72^{+0.98}_{-1.38}$	3.67±0.131	25.3/17
ASCA GIS (1997)	2.05±0.11	1.99±0.175	60.3/58
XMM-Newton EPIC pn (2000-01)	2.46±0.03	2.25±0.037	235/240

OPTICAL AND IR OBSERVATIONS

RE J2248-511 was observed on 2000 October 19-24 using the South African Astronomical Observatory's 1.9m Radcliffe telescope. Three observations were made with the grating spectrograph and SITe CCD one night apart and measurements of the IR magnitude in the J,H,K bands were made on a single night with the infrared photometer. Spectra were taken using both a wide (700 μm) and a narrow (300 μm) slit with overlapping red and blue gratings ($\lambda_{central}$ = 4600,7800Å). Arc spectra were taken before and after every target and every standard spectrum. The spectra have been extracted using the Image Reduction and Analysis Facility (IRAF).

RESULTS FROM THE OPTICAL SPECTROPHOTOMETRY

Seeing, humidity and cloud cover were extremely variable during the observing period and consequently only one of the nights we consider to be photometric. The spectra were not taken at the parallactic angle, but there appears to have been little or no loss of blue light since the spectra become stronger towards the blue end.

The Broad Line Region

Both Hα and Hβ are best fitted with three gaussians with broad components of FWHM approximately 3700Å. The ratio of Hα to Hβ line flux, excluding the narrow-line component, is Hα/Hβ = 2.67. The line parameters we measure are consistent with those measured in the spectrum during 1991 (Mason et al. 1995; Hα was not observed). The Hβ measurements are in approximate agreement with the 1992 measured values (Grupe et al. 1999).

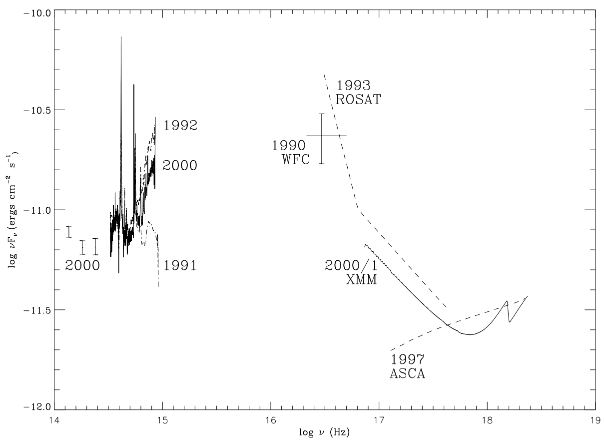

Fig. 5. Spectral energy distribution from optical to X-ray for RE J2248-511 including all available optical, IR and UV data and best-fitting X-ray models spanning 1990 to 2001.

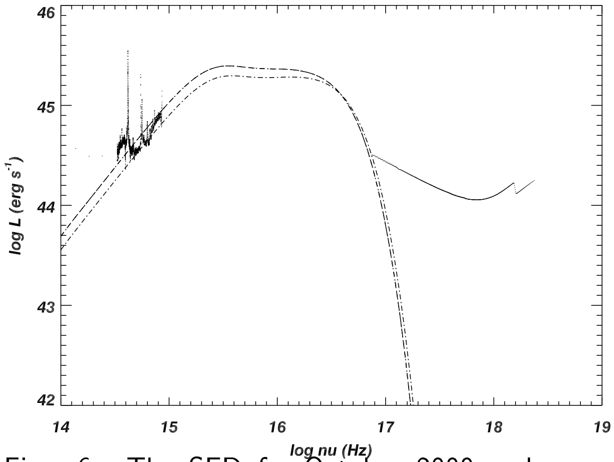

Fig. 6. The SED for October 2000 and two Comptonised disk models with $\dot{M} = 0.8 M_{Edd}$ and $\cos(i) = 0.8$. The model represented by the dashed line is for black hole mass $M = 10^8$ M$_\odot$; the dot-dashed line is for $M = 10^{7.9}$ M$_\odot$.

Optical Variability and the Big Blue Bump

In Figure 5 all available data for RE J2248-511 is plotted to show the various flux levels that have been observed. We find that the slope of the optical spectrum in the SED plot lies in between the slopes measured in 1991 (Mason et al. 1995) and 1992 (Grupe et al. 1998). Since the soft X-ray data from 2000/01 can be fit with a multi-temperature disk blackbody model, we investigated the possibility of the entire optical to soft X-ray flux originating in an accretion disk. We use Comptonised accretion disk models developed by Czerny & Elvis (1987) and fitted these to the spectral energy distribution for October 2000. Two model fits are shown with the data in Figure 6. These models can fit the optical slope reasonably well and are not inconsistent with the soft X-ray data. These data require models with masses of order $M = 10^8$ M$_\odot$, high accretion rates of $\dot{M} \sim 0.8 M_{Edd}$ and high disk inclination angles of $\cos(i) \geq 0.8$.

DISCUSSION

Of the physical models for the X-ray spectrum tested here we are unable to constrain the key parameters in any case. The power-law-plus-reflection model is able to fit the data only with a high reflection fraction. This multiple reflection scenario could conceivably occur if there were a large number of clouds above or around the X-ray source which could reflect the emission but not transmit it. Alternatively, the accretion disk could be of varying height, like ripples on a pond, each ripple reflecting the incoming X-rays (Ballantyne, Ross & Fabian 2001). However, we do not detect strong Iron emission or the neutral Iron edge at 7.1 keV which are characteristic of strong reflection, except where the reflecting material is highly ionised. This Seyfert lies at the boundary between the quasar and Seyfert galaxy luminosities. Seyfert galaxy X-ray spectra typically show disk features including Iron lines and a reflection component which are less common in quasars. This is thought to be because the disk material becomes fully ionised and does not produce emission lines (eg. Matt et al. 1993). Though we do not see low ionisation Iron Kα emission in these data, the upper limits on its equivalent width are typical of lines already observed in many Seyfert galaxies. Therefore reflection is unlikely to be making a strong contribution to the X-ray continuum flux in this source.

The double Comptonisation model requires both optically thick and optically thin material, each being illuminated by different temperature photons. A change in optical depth of the material could explain the change between the flat *ASCA* spectrum and the very soft EPIC pn spectrum. This scenario has also been suggested for the Seyfert 1 galaxy 1H 0419-577 (Page et al. 2001) and is discussed for this source in Breeveld et al. (2001). This model, however, could not account for any correlation with the optical flux.

Currently there is insufficient data to distinguish between many of the models and a 2-blackbodies-plus-power-law model remains the best representation of this data.

From the variability time-scale we estimate the size of the region emitting the flux of the soft X-ray excess to be $\leq$3.4 l.y. or $\leq$1 pc, which only locates it to at or within the BLR.

That both the 2000 optical and soft X-ray slopes are steep and both wavebands show great variability suggests a link between them. The optical to soft X-ray spectral energy distribution for 2000 is not inconsistent with Comptonised accretion disk models. Contrary to the proposed NLS1 scenario, the data are best fitted with intermediate to high black hole masses, whilst still favouring the high accretion rates suggested for NLS1 galaxies. Therefore, it is not necessary for a black hole to have a low mass for the formation of an ultrasoft X-ray excess. The relatively high velocity of the BLR may, however, be linked with the black hole mass, perhaps as a consequence of the increased gravitational potential. The mass and accretion rate we estimate from this modelling implies an inner disk effective temperature of $\sim$25 eV assuming a standard disk model, lower than that fitted to the lower-temperature soft X-ray component. However, the temperature measured in the X-ray blackbody models is the colour temperature which may be much higher than the effective temperature if the spectrum is modified by electron scattering (eg Titarchuk & Shrader 2002).

CONCLUSIONS

This *XMM-Newton* observation has shown yet more dramatic activity in the soft X-ray spectrum of RE J2248-511, whilst the hard X-ray power law remains constant. We find that both Comptonisation and reflection models, while appearing to fit the X-ray spectrum well, cannot be constrained, and a model consisting of 2 blackbodies and a power-law remains the best representation of these data. The 2000 optical to soft X-ray spectral energy distribution may be consistent with a face-on Comptonised accretion disk accreting at a rate approaching the Eddington limit onto a 10^8 M$_\odot$ black hole. Observations at UV wavelengths are needed to tie down the parameters of any such model, and more simultaneous multi-wavelength data are needed to confirm the correlation between optical and soft X-ray variability and the presence of a single Big Blue Bump.

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email address of R. L. C. Starling rlcs@mssl.ucl.ac.uk
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