Do the spectral energy distributions of type 1 active galactic nuclei show diversity?

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ABSTRACT

We create broad-band spectral energy distributions (SEDs) of 761 type 1 active galactic nuclei (AGN). The Scott et al. sample, created by a cross-correlation of the optical Sloan Digital Sky Survey Data Release 5 quasar catalogue and the 2XMMi catalogue of serendipitous X-ray sources, is further matched with the Faint Images of the Radio Sky at Twenty-cm catalogue of radio sources, the mid-infrared (MIR) Wide-field Infrared Survey Explorer all-sky data release, the Two Micron All Sky Survey near-infrared point source catalogue, the UKIRT Infrared Deep Sky Survey Data Release 9 Large Area Survey and the Galaxy Evolution Explorer all-sky and medium ultraviolet (UV) imaging surveys. This allows broad-band SEDs including up to 19 flux measurements covering log ν ∼ 9.2–18.1 to be created. We investigate variations in the SED shape by binning a subsample of 237 AGN with the best quality SEDs according to their X-ray spectral parameters, their quasar subtype and physical parameters such as luminosity, black hole mass and Eddington ratio. The AGN subpopulations show some significant differences in their SEDs; X-ray absorbed AGN show a deficit of emission at X-ray/UV frequencies and an excess in the MIR consistent with absorption and re-emission, radio-loud AGN show increased radio and X-ray emission consistent with the presence of a jet component in addition to the emission seen from radio-quiet AGN and the SEDs of narrow-line Seyfert 1s only differ from other type 1s in the X-ray regime, suggesting any physical differences are limited to their X-ray emitting region. Binning the AGN according to underlying physical parameters reveals more subtle differences in the SEDs. The X-ray spectral slope does not appear to have any influence or dependence on the multiwavelength emission in the rest of the SED. The contribution of X-rays to the bolometric luminosity is lower in higher luminosity sources, and relatively more emission in the optical/UV is seen in AGN with higher X-ray luminosities. Variations in the relative flux and peak frequency of the big blue bump are observed and may suggest higher inner disc temperatures with increasing accretion rates. Overall, we find that the diversity in the SED shapes is relatively small, and we find no apparent single driver for the variations.

Key words: accretion, accretion discs – galaxies: active – quasars: general – infrared: galaxies – ultraviolet: galaxies – X-rays: galaxies.

1 INTRODUCTION

Active galactic nuclei (AGN) have high bolometric luminosities (10^{44}–10^{48} erg s^{-1}) and emit across the entire electromagnetic spectrum. The amount of energy output at different frequencies is described by a spectral energy distribution (SED). It shows features originating from separate physical processes occurring in different regions around the central, supermassive black hole. The radio emission of AGN contributes very little to the bolometric output, even in radio-loud quasars (RLQ) where it is typically 100–1000 times greater than that of radio-quiet quasars (RQQ) and originates from synchrotron emission in their relativistic jets. A broad ‘hump’ of infrared (IR) emission at 2–25 μm is thought to be due to thermal re-processing by dust surrounding the black hole (Rees et al. 1969; Rieke 1978), possibly in the torus (Antonucci & Miller 1985). The ultraviolet (UV) and optical emission from AGN is dominated by the ‘big blue bump’ (BBB), which is attributed primarily to thermal emission from the accretion disc (Shields 1978; Malkan & Sargent 1982; Czerny & Elvis 1987). The X-ray emission is thought to be produced mainly by the inverse Compton scattering of low-energy UV photons from the accretion disc by relativistic electrons in the...
corona (Haardt & Maraschi 1993). It appears in the spectrum as a simple power law described by $P_\gamma \propto E^{-\Gamma}$, where $\Gamma$ is the photon index (Mushotzky et al. 1980) and may be modified by reflection in the accretion disc (Pounds et al. 1990). $\gamma$-rays have also now been detected from a number of AGN (Wagner 2008), but contribute very little to the total luminous output in non-blazar type 1 AGN. An accurate knowledge of the relative strengths and shapes of the different components in AGN SEDs can aid the understanding of the physical processes occurring in the object. In particular, understanding how the SED shape changes with underlying physical parameters, such as the mass of the black hole, $M_{\text{BH}}$, and the accretion rate, can help us to better understand the overall accretion process.

Constructing complete SEDs requires data in multiple wavebands, necessitating observations from many different instruments and observatories, both space borne and ground based. Consequently this process has historically been very time consuming. The seminal work which created full SEDs for 47 quasars (29 RQQ and 18 RLQ) was that of Elvis et al. (1994) and included X-ray to radio data. Variation in the SEDs of different objects was found, and the mean energy distribution was presented. With the greater availability of multiwavelength data, larger samples of SEDs can now be created. Richards et al. (2006) constructed SEDs of 259 quasars using photometry from the X-ray through to the radio band. More recently, Lusso et al. (2012) have constructed SEDs of 545 X-ray selected type 1 AGN, and Elvis et al. (2012) present a mean SED of 413 type 1 AGN, both from the XMM–Newton deep field. Shang et al. (2011) have created SEDs of a smaller sample of objects, with a complicated selection function, but they include high-resolution UV/optical and mid-infrared (MIR) spectra in addition to photometry in the radio, far-infrared (FIR) and near-infrared (NIR) bands.

Jin et al. (2012a) studies the optical to X-ray SEDs of a small sample of 51 type 1 AGN, including 12 narrow-line Seyfert 1 (NLS1), using high-quality spectra from the Sloan Digital Sky Survey (SDSS; York 2000) and XMM–Newton. They fit their partial SEDs with a physically motivated model incorporating the disc emission, Comptonization and the X-ray power law, and derive physical quantities such as the power-law slope, $\Gamma$, the 2–10 keV X-ray luminosity, $L_X$, the bolometric luminosity, $L_{\text{bol}}$, bolometric correction factors, $\kappa$, the Eddington ratio, $L_{\text{bol}}/L_{\text{Edd}}$, and $\alpha_{\text{UV}}$, directly from the model fit. Mean SEDs were presented, binned according to their physical parameters. It was found that the SED changes are similar for most parameters except $L_{\text{bol}}$, likely because the SED shape does not depend solely on one key parameter but ultimately depends on a combination of $L_{\text{bol}}/L_{\text{Edd}}$ and $M_{\text{BH}}$. Hao et al. (2012) investigate how the NIR–UV SED shape varies with respect to $z$, $L_{\text{bol}}$, $M_{\text{BH}}$ and $L_{\text{bol}}/L_{\text{Edd}}$ using a subsample of 200 radio-quiet type 1 AGN from XMM–COSMOS. They find no dependence of the SED shape on these parameters. Krawczyk et al. (2013) create a mean NIR–UV SED of 108 184 type 1 AGN and investigate the SED dependence on UV parameters. They find that the SEDs for lower UV luminosity AGN show harder $\alpha_{\text{UV}}$, redder optical continua and lower amounts of hot dust.

In this work we create broad-band SEDs for the sample of 761 type 1 AGN described in Scott et al. (2011, hereafter S11). The sample was created by a cross-correlation of the serendipitous X-ray source catalogue 2XMMi (Watson et al. 2009) and the optical SDSS Data Release 5 quasar catalogue (Schneider et al. 2007). We also include photometry in the radio, MIR, NIR and UV bands. The sample includes sources representative of typical type 1 AGN, and the large number allows us to investigate how the SED shape changes with physical parameters spanning a large range of values. We construct average broad-band SEDs, binned according to their X-ray spectral properties, $\Gamma$ and the inclusion of spectral components, redshift, their quasar subtype including RL, radio power-law slope, $\Gamma$, and $2–10$ keV X-ray luminosity (bottom), which were first presented in S11. These are compared to the distributions for the subsample of 237 sources considered later in this paper (red, dashed), plotted with a small, arbitrary offset for clarity.

### Figure 1

Shown with the black, solid lines are the distributions of the best-fitting power-law slope, $\Gamma$ (top), and $2–10$ keV X-ray luminosity (bottom), which were first presented in S11. These are compared to the distributions for the subsample of 237 sources considered later in this paper (red, dashed), plotted with a small, arbitrary offset for clarity.

#### 2 DATA

This paper studies the multiwavelength properties of a large sample of 761 type 1 AGN for which a comprehensive X-ray spectral analysis was presented in S11. This included estimates of the power-law slope $\Gamma$ from the best-fitting spectral model, and estimates of the unabsorbed $2–10$ keV X-ray luminosity, $L_X$. The distributions of these two parameters are shown in black in Fig. 1. For the analysis in this paper we estimate the X-ray flux in narrow bands using the best-fitting spectral model, and convert them to monochromatic flux estimates at 0.5, 1.0 and 5.0 keV. These values are corrected for Galactic absorption, assuming an $N_{\text{HI}}$ value taken from the H I map of Dickey & Lockman (1990).

1. $\alpha_{\text{UV}} = 0.38 \log (f_X/f_\lambda)$, where $f_X$ is the X-ray flux at 2 keV and $f_\lambda$ is the optical flux at 2500 Å.

2. $R_L = f_R/f_\lambda$, where $f_R$ is the radio flux at 5 GHz and $f_\lambda$ is the optical flux at 4400 Å.
Each of the sources has optical photometry in the five SDSS ugriz bands. The catalogue point spread function (PSF) magnitudes are first corrected for Galactic extinction using values from the maps of Schlegel, Finkbeiner & Davis (1998) and then converted into the AB system (Oke & Gunn 1983). The magnitudes (and their associated errors) are converted into a flux density by equation (1) where $F_0 = 3631 \text{ Jy}$:

$$\text{Flux (Jy)} = F_0 \times 10^{-0.4m}.$$  

(1)

Radio fluxes for the sources at 1.4 GHz were obtained from the Faint Images of the Radio Sky at Twenty-cm (FIRST) catalogue (Becker, White & Helfand 1995). A 20 arcsec matching radius was used in order to ensure that any extended emission from the source was included, and the radio fluxes from any multiple matches were summed. 104 sources had a detection in FIRST and for the 613 sources with no detection, five times the rms at the source position was used as an upper limit. 44 sources did not lie in the sky area covered by the FIRST survey. For sources with a detection, the error on the integrated flux was taken to be the rms value at the source position. In the case of multiple detections, the rms values for each are added in quadrature.

NIR fluxes were obtained from the Two Micron All Sky Survey (2MASS) Point Source Catalogue (Cutri et al. 2003) using a 2 arcsec matching radius. 166 matches were found, with no sources having duplicate detections. Only two sources have separations greater than 1 arcsec, and both are less than 1.5 arcsec. Approximately 75 per cent of the source detections are part of the ‘faint extension’ and have magnitudes as faint as 17.6 (J), 17.8 (H) and 16.3 (K). The magnitudes and corresponding errors given in the catalogue were converted to fluxes using equation (1) where $F_0$ for each of the three bands is: $J$: $F_0 = 1594 \pm 27.8 \text{ Jy}$; $H$: $F_0 = 1024 \pm 20.0 \text{ Jy}$; $K$: $F_0 = 666.7 \pm 12.6 \text{ Jy}$. The NIR data were excluded for sources with catalogue flags indicating poor photometry. The sample was also cross-correlated with the UKIRT Infrared Deep Sky Survey (UKIDSS; Lawrence et al. 2007), which uses the Wide-Field Camera (WFCAM; Casali et al. 2007) on the United Kingdom Infrared Telescope (UKIRT). The Large Area Survey (LAS) from Data Release 9 (DR9) was searched for matches within a 1 arcsec radius of the optical source positions. 353 sources had data in at least one of the four UKIDSS photometric bands $y'j'hk$. The default point-source aperture-corrected magnitudes and errors were extracted from the archive (Hamblly et al. 2008) and were converted to fluxes using equation (1) where $F_0$ for each of the four bands is: $y$: $F_0 = 2026 \text{ Jy}$; $J$: $F_0 = 1530 \text{ Jy}$; $H$: $F_0 = 1019 \text{ Jy}$; $K$: $F_0 = 631 \text{ Jy}$. For 72 sources NIR data are available from both 2MASS and the deeper UKIDSS survey. In these cases we use the UKIDSS data in preference to any 2MASS data for individual bands, due to the errors on the photometry being an order of magnitude lower. The dispersion between the flux estimates from each survey is $\lesssim 0.2 \text{ mag}$. Combining both data sets, 408 sources have a flux estimate in the $yj'hk$ bands (309 also include a $y$-band flux).

The sample was cross-correlated with the All Sky Data Release (Cutri et al. 2012) from Wide-field Infrared Survey Explorer (WISE) to obtain MIR fluxes. A 5 arcsec matching radius was used giving 819 matches corresponding to 754 unique objects. In cases where two WISE detections were matched to the same SDSS coordinates, the one with the largest separation was excluded, provided the closest match had a separation $<1 \text{ arcsec}$. Any further double matches within the 6 arcsec resolution limit were excluded. This gave a final sample where 754 sources have a WISE detection, 98 per cent of which have a separation $<2 \text{ arcsec}$ from the optical position. The four broad-band WISE magnitudes and associated errors were converted to fluxes by equation (1) using the zero-point fluxes $W1$: $F_0 = 306.682 \pm 4.600 \text{ Jy}$; $W2$: $F_0 = 170.663 \pm 2.600 \text{ Jy}$; $W3$: $F_0 = 29.045 \pm 0.436 \text{ Jy}$; $W4$: $F_0 = 8.824 \pm 0.124 \text{ Jy}$. The WISE data were excluded if the photometry was flagged as poor by the catalogue. 46 sources were affected in at least one of the WISE bands, but only 16 unique sources were affected in all four.

UV fluxes were obtained from Galaxy Evolution Explorer (GALEX) GR6 data using casjobs. A matching radius of 2 arcsec, as recommended by Morrissey et al. (2007), yielded 1664 matches to 645 unique sources. We limit the detection list to those from All-Sky Imaging Survey (AIS) or Medium Imaging Survey (MIS) observations as their magnitude limits are well defined. We use the MIS detection where both are available. We calculate the likelihood ratio, $L$, and the reliability, $R$, of each detection being the correct match (Sutherland & Saunders 1992; equation 2) and choose the detection with the highest value of $R$ as the most appropriate. All detections have $R > 50$ per cent:

$$L = \frac{Q(<m)\exp(-r^2/2)}{2\pi\sigma_1\sigma_2 N(<m)}; \quad R_j = \frac{L_j}{\sum L_i + [1 - Q(<m)]}.$$  

(2)

This gives a final sample of 590 unique sources with a UV detection. The UV magnitudes are corrected for Galactic reddening using the reddening law $A_{UV} = R_{UV} E(B-V)$ (Cardelli, Clayton & Mathis 1998) where the $E(B-V)$ values were obtained from the maps of Schlegel et al. (1998) and $R_{UV} = 8.24$ (Wyder et al. 2007). UV fluxes are calculated using equation (1) where $F_0 = 3631 \text{ Jy}$. 358 sources have a detection in both the NUV and FUV bands, 224 sources only have a detection in the NUV and eight have FUV data only.

Table 1 lists the percentage of the sample which have a flux measurement in each of the wavebands considered in this analysis.

3 Average Spectral Energy Distributions

Rest-frame monochromatic luminosities are calculated at each wavelength and for each individual object using $\nu L_{\nu} = 4\pi d_l^2 \nu F_{\nu}$, where $\nu$ is the observed frequency, $F_{\nu}$ is the observed flux and $d_l$ is the luminosity distance calculated from the redshift of the source assuming a flat cosmology with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.3$ and $\Omega_{\Lambda} = 0.7$ (Spergel et al. 2003). An example of a single AGN SED plotted using log $\nu$ on the x-axis (in units of log Hz) and log $\nu L_{\nu}$ on the y-axis (in units of log erg s$^{-1}$) is shown in Fig. 2. Luminosity measurements with errors are plotted in different colours depending on the source of the data. Measurements with bad photometry flags are excluded completely, whilst upper limits are plotted as triangles. It shows many of the typical features expected in the SED of a type 1 AGN including power-law emission in the X-ray regime, in this case with a flat spectral slope of $\Gamma \sim 1.6$, a gap in the SED between the X-ray and UV emission which cannot be sampled due to absorption by the Milky Way, the BBB at (log) frequencies of 14.5–15.5, an inflection point in the NIR at log $\nu \sim 14.5$, which is thought to correspond to the sublimation temperature of dust grains (Sanders et al. 1989), the IR hump at frequencies lower than log $\nu \sim 14.5$, which appears to be due to the superposition of two blackbodies with different peak temperatures, possibly related to emission from the hotter, inner edge and the cooler, outer edge of the torus (Calderone, Sabbato & Ghisellini 2012), another gap in

3 http://galex.stsci.edu/casjobs/
Table 1. The observed frequencies of the 19 wavebands used in the multiwavelength catalogues and the percentage of the 761 sources with a flux measurement in each. Upper limits which are not used in the SED creation and detections with bad photometry are not included in these numbers.

<table>
<thead>
<tr>
<th>Waveband</th>
<th>log $\nu$</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>X-ray</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(XMM)</td>
<td>Hard</td>
<td>18.08</td>
</tr>
<tr>
<td></td>
<td>Soft</td>
<td>17.38</td>
</tr>
<tr>
<td></td>
<td>Very soft</td>
<td>17.08</td>
</tr>
<tr>
<td>UV</td>
<td>FUV</td>
<td>15.29</td>
</tr>
<tr>
<td>(GALEX)</td>
<td>NUV</td>
<td>15.11</td>
</tr>
<tr>
<td>Optical</td>
<td>$\mu$</td>
<td>14.93</td>
</tr>
<tr>
<td>(SDSS)</td>
<td>$g$</td>
<td>14.80</td>
</tr>
<tr>
<td></td>
<td>$r$</td>
<td>14.68</td>
</tr>
<tr>
<td></td>
<td>$i$</td>
<td>14.59</td>
</tr>
<tr>
<td></td>
<td>$z$</td>
<td>14.52</td>
</tr>
<tr>
<td>NIR</td>
<td>$Y$</td>
<td>14.46</td>
</tr>
<tr>
<td>(UKIDSS)</td>
<td>$J$</td>
<td>14.38</td>
</tr>
<tr>
<td>and 2MASS</td>
<td>$H$</td>
<td>14.26</td>
</tr>
<tr>
<td></td>
<td>$K$</td>
<td>14.26</td>
</tr>
<tr>
<td></td>
<td>W1</td>
<td>13.95</td>
</tr>
<tr>
<td>(WISE)</td>
<td>W2</td>
<td>13.81</td>
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<tr>
<td></td>
<td>W3</td>
<td>13.40</td>
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<tr>
<td></td>
<td>W4</td>
<td>13.13</td>
</tr>
<tr>
<td>Radio</td>
<td>(FIRST)</td>
<td>9.16</td>
</tr>
</tbody>
</table>

aWavelengths correspond to the UKIDSS survey.
bWavelengths correspond to the 2MASS survey.

The bolometric luminosity of each source is determined by a simple numerical integration according to equation (3), in which the $L_{\nu}(i)$ values are taken from the 5000 interpolation points and $\Delta \nu(i)$ is the width of each bin, unevenly sized in linear space:

$$L_{\text{bol}} = \int_0^{+\infty} L_{\nu} \, dv \sim \sum_{i} L_{\nu}(i) \, \Delta \nu(i).$$

In the interpolation we use a simple straight line (power law in linear space) to interpolate across the extreme ultraviolet (EUV) gap. However, this may be unrepresentative of the real SED shape in this frequency range leading to an incorrect estimate of $L_{\text{bol}}$. In order to investigate the size of this effect, we recalculate the bolometric luminosity of the sources using different interpolation shapes over this region. The first, which gives an increased $L_{\text{bol}}$ measurement maintains the highest of the fluxes at the edge of the gap (UV or X-ray) across the whole range, whilst the second maintains the lowest of the fluxes across the gap and gives a lower $L_{\text{bol}}$ measurement. The average differences between these extreme estimates and the estimate used in this analysis are $\lesssim 0.2$ dex for 76 per cent of the sources ($\lesssim 0.25$ dex for 88 per cent).

For 104 of the sources a radio detection is available and therefore the SED interpolation, and hence $L_{\text{bol}}$ determination, includes the frequency range between WISE band 4 and radio. For the remaining 657 sources without a radio detection, this large frequency range is not considered. The difference between $L_{\text{bol}}$ estimates, both including and excluding this range is $\lesssim 0.1$ dex for 93 per cent of sources, making this effect much smaller than the differences introduced by variations in the interpolation shape used over the EUV gap.

Our $L_{\text{bol}}$ estimates are in good agreement with literature values. Bolometric luminosities derived from optical monochromatic luminosities and bolometric correction factors from Richards et al. (2006) are given by Shen et al. (2008). These values are plotted against our estimates in Fig. 3 (black points) and show a tight correlation and good agreement. Estimates using the $2–10$ keV luminosity from the original analysis in S11 and the luminosity-dependent bolometric correction of Marconi et al. (2004) are also shown in Fig. 3 (red points). These estimates show a larger scatter, but are

Figure 2. The rest-frame SED of 2XMM J120857.9+454035. It includes radio data from FIRST (black), MIR data from WISE (orange), NIR data from 2MASS (pink), optical data from SDSS (red), UV data from GALEX (light blue) and X-ray data from XMM–Newton (dark blue). Filled circles with error bars correspond to flux measurements. Triangles denote upper limit estimates.
plying that each bin contributes $\sim 10^4$ SED shapes. This is due to different normalizations but is simply a result of different frequency, rather than absolute values and none of the dispersion. We use equations (9)–(11) from Elvis et al. (2012) which are logical information with which to correctly select an appropriate host galaxy template, we can only estimate the galaxy contribution by their bolometric luminosity, we expect in the interpolation; figures, where the constant depends upon the width of the bins used in the interpolation; $\Delta \log \nu = 0.002$. It has the value $C = -2.34$ implying that each bin contributes $\sim 1/200th$ of $L_{\text{bol}}$. By normalizing the individual AGN SEDs by their bolometric luminosity, we expect the SEDs to have approximately the same $y$-axis values. This means that the figures are comparing the relative levels of emission at each frequency, rather than absolute values and none of the dispersion is due to different normalizations but is simply a result of different SED shapes.

Our sample includes luminous quasars with bolometric luminosities greater than $7 \times 10^{44}$ erg s$^{-1}$. The possible contamination from the host galaxies is therefore not expected to be large. As we have no direct observational data for the host galaxies, nor any morphological information with which to correctly select an appropriate host galaxy template, we can only estimate the galaxy contribution. We use equations (9)–(11) from Elvis et al. (2012) which are adapted from Marconi & Hunt (2003) to include a redshift dependence, to estimate the luminosity of the host galaxy in the NIR. The percentage of the total luminosity which can be attributed to the host galaxy ranges from 0.1 to 1.3 per cent in the $J$ and $K$ bands to 0.1–1.5 per cent in the $H$ band where the host contribution is known to be largest. However, this assumes that each AGN is accreting at the Eddington luminosity, and whilst this is frequently used to determine the minimum correction to be applied (e.g. Richards et al. 2006), here we relax this assumption. If each AGN is instead accreting at only 10 per cent of Eddington, we find that the host galaxy contributes up to 11 per cent in the $H$ band. This means that the host contribution can move the SEDs we plot by at most 0.04 on the $y$-axis, peaking in the NIR $H$ band, and decreasing rapidly at frequencies $\log \nu < 14.0$ and $\log \nu > 14.6$. This shift is lower than the typical width of the SEDs we plot, however, we exercise caution when interpreting any differences in the SED shape at NIR frequencies.

In Fig. 4 we plot the average SED of the 761 sources in the sample. On the $y$-axis we plot the median log($L_\nu/L_{\text{bol}}$) + $C$ value of the sources included in the sample at that particular log $\nu$ value (green line) along with the 32nd, 68th, 5th and 95th percentiles, which correspond to $\sigma$ and $2\sigma$ error boundaries (blue and red lines). Also shown in black is the arithmetic mean of the SED values where the width of the line corresponds to the standard error ($\sigma = \sigma/\sqrt{N}$) at that frequency. The mean gives a similar SED shape to the median in this case, but using the median and percentiles is more effective at rejecting outliers and gives a better representation of the dispersion in the SEDs.

Between the radio and W4 band, and within the EUV gap, the SEDs consist only of interpolation points and no real flux measurements over a large frequency range. Whilst these regions are considered in the determination of $L_{\text{bol}}$ to avoid an underestimate, we do not plot them in the average SED. The rest-frame frequency range covered by each source’s SED varies due to their redshift, so at either end of the SED, and at the edges of the EUV gap, the number of sources considered decreases from $N \rightarrow 0$ giving an increased dispersion. Since accurate median and percentile values cannot be calculated from a low number of sources, we trim the portions of the SED where the number of sources included at that frequency falls below 10 per cent of the initial number included in the subsample. For subsamples with less than 50 sources, we trim the SEDs when the number included falls below 5. In order to give an accurate interpolation of the SED, it is important to include as many real flux measurements as possible in order for the SED to be well sampled across the full frequency range. However, only 10 sources in the sample have a flux measurement (not including upper limits) in each of the 19 wavebands. This is
mainly due to low percentage coverages in the radio, FUV and NIR bands (see Table 1). We therefore select a subsample of AGN in which the majority of the SED is sampled with real flux measurements. We still require an FUV flux as this probes a particularly important part of the SED and occurs at one end of the high-energy SED gap. However, we no longer require a radio, W3 or W4 flux. The NIR region of the SED is important for mapping the inflection point at $\log \nu \sim 14.5$, but this region has a low coverage, only $\sim 60$ per cent. We create an average SED of 196 sources which include each of the $J$, $H$ and $K$ bands (not necessarily the $Y$ band). This is compared to a sample of 32 sources which include at least one NIR measurement, (but not all three of $J$, $H$ and $K$), and another sample of 86 sources which do not include any. The SEDs which include at least some NIR data clearly show the inflection point in the SED, but this feature is not apparent in the SED which includes no NIR data. This important feature appears to be missed if no real flux measurements are included over this range. However, we note that the lack of a NIR inflection point may not simply be due to data sampling alone and could be a real feature indicative of a population of ‘hot-dust poor’ type 1 AGN (Hao et al. 2010).

We create a final subsample including 237 AGN, 31 per cent of the original sample. They are required to include flux measurements in each of the three X-ray bands, each of the two UV bands, all five optical bands, at least one of the $J$, $H$ or $K$ bands, and the W1 and W2 MIR bands. Although some of the flux bands are not required, 83 per cent of these sources do include all of $JHK$, 58 per cent include all of $YJHK$, 96 per cent have a W3 flux, 71 per cent have a W4 flux and 16 per cent include a radio flux. We also exclude sources whose best-fitting X-ray spectral model in the original analysis of S11 required intrinsic absorption. We identify 10 AGN in the sample with possible dust reddening due to a relative colour $\Delta(g-i) > 0.2$ after correction for Galactic reddening using a Small Magellanic Cloud (SMC) extinction curve, and a continuum shape of $\Delta(u-r) > \Delta(g-i) > \Delta(r-z)$ (See Richards et al. 2003). We do not exclude these AGN from our final sample, but their presence does not impact our overall results.

The median SED of the final subsample is shown in Fig. 5 plotted in red and is compared to the median SED produced from all 761 sources in the original sample, shown in black. They are in good agreement suggesting that the results we obtain from our good quality subsample are applicable to type 1 AGN in general. The reduced sample is slightly more biased towards lower $z$ and lower $L_{\text{bol}}$ objects, but still covers a large range in these parameters ($z$: 0.11–3.29, $L_{\text{bol}}$: 44.85–48.10). In Fig. 1 we compare the $\Gamma$ and $L_X$ distributions of the subsample of 237 AGN (red, dashed) to the full sample of 761 AGN first reported in S11. A Kolmogorov-Smirnov (KS) test finds the $\Gamma$ distributions not to be statistically different (significance $= 0.52$), but as noted above, the $L_X$ distributions are significantly different (KS significance $= 4.7 \times 10^{-3}$).

Also shown in Fig. 5 are average SEDs from the literature which have been reproduced here on an arbitrary scale, with an artificial separation between them for clarity. The mean SED of 29 X-ray bright, blue, RQQ from Elvis et al. (1994) is plotted in orange, the mean SED of 259 mostly radio-quiet SDSS quasars from Richards et al. (2006) is plotted in blue and the median SED of 27 optically bright RQQ at $z < 0.5$ from Shang et al. (2011) is plotted in green. Our mean SED is in good agreement with these literature SEDs, particularly in the optical/UV region where the ‘small blue bump’ of Balmer continuum and Fe II line emission can be clearly seen. It is a good match to the Richards et al. (2006) mean SED and the underlying continuum of the Shang et al. (2011) SED. Our SED shows greater X-ray emission and lower MIR emission compared with the Richards et al. (2006) SED. This is related to the selection biases of each sample as ours is biased against X-ray weak SDSS quasars and theirs required a Spitzer Infrared Array Camera (IRAC) detection in all four MIR bands.

4 SED VARIATIONS

In this section we investigate variations in the average SED shape of type 1 AGN using the 237 sources with SEDs which are well sampled over a large frequency range. We bin the sources according to their X-ray spectral properties, redshift, their quasar subtype and physical parameters. The definitions of the further subsamples created for this analysis are listed in Table 2 along with the number of sources included in each. They are defined such that the parameters are divided in a physically interesting way and where possible the number of sources included in each bin is approximately equal. This ensures that any dispersion caused in the SED due to the numbers of sources included is the same for each subsample. The average SEDs produced for these subsamples are shown in Figs 6–8. In each case the SEDs of the different subsamples are shown in different colours. The median value of log($L/L_{\odot}$) is plotted, bounded by the 32nd and 68th percentiles, hence the width of each SED corresponds to a 1$\sigma$ error boundary. The ends of the SEDs are trimmed when the number of sources falls below five, or 10 per cent of the initial number, as described in Section 3. The radio portion of the SED is not shown in the majority of cases for clarity, but unless stated otherwise it is consistent between the subsamples or there is limited data available. The main panel of each figure includes an indicative bar showing the frequencies and regions of the SED which correspond to each broad waveband range for a source at $z = 0$. In Fig. 8 and the top panel of Fig. 7 we also indicate the rest-frame frequency of the peak of the BBB with a 1$\sigma$ error bar determined from the dispersion of the individual BBB peaks of the included SEDs. The peak frequency we indicate is that of the peak in the median SED (which may not directly correspond to the peaks as visible in the 68th percentile). The top panel of each figure indicates how many individual AGN have been used in the SED creation at that particular frequency.

Figure 5. This figure compares the average SEDs produced in this work to average SEDs from the literature. Plotted in black is the median SED produced from all 761 sources considered in this paper and plotted in red is the median of the 237 sources with well sampled SEDs which are made up the subsample of AGN considered in more detail in Section 4. Plotted in orange is the mean SED of 29 RQQ from Elvis et al. (1994), in blue is the mean SED of 259 SDSS quasars from Richards et al. (2006) and in green is the median SED of 27 RQQ from Shang et al. (2011). They are plotted on an arbitrary y-axis and have been artificially separated for clarity.
Table 2. The 237 sources which have a well-sampled SED as described in Section 3 are binned according to the different parameters listed below. The definition of each of the sub-bins and the number of sources included in each are listed. Average SEDs binned according to these parameters are shown Figs 6–8.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Definition</th>
<th>No. sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma$</td>
<td>$\Gamma &lt; 1.8$</td>
<td>78</td>
</tr>
<tr>
<td></td>
<td>$1.8 &lt; \Gamma \leq 2.2$</td>
<td>109</td>
</tr>
<tr>
<td></td>
<td>$\Gamma &gt; 2.2$</td>
<td>50</td>
</tr>
<tr>
<td>Soft X-ray excess</td>
<td>Power law</td>
<td>195</td>
</tr>
<tr>
<td></td>
<td>Power law + blackbody</td>
<td>42</td>
</tr>
<tr>
<td>X-ray absorption</td>
<td>Power law</td>
<td>237</td>
</tr>
<tr>
<td></td>
<td>Absorbed power law</td>
<td>12$^a$</td>
</tr>
<tr>
<td>Redshift</td>
<td>$z &lt; 0.7$</td>
<td>97</td>
</tr>
<tr>
<td></td>
<td>$0.7 &lt; z \leq 1.2$</td>
<td>67</td>
</tr>
<tr>
<td></td>
<td>$1.2 &lt; z$</td>
<td>73</td>
</tr>
<tr>
<td>Broad lines</td>
<td>NLS1</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>Non-NLS1</td>
<td>94</td>
</tr>
<tr>
<td>$R_L$</td>
<td>RQQ</td>
<td>182</td>
</tr>
<tr>
<td></td>
<td>RLQ</td>
<td>25</td>
</tr>
<tr>
<td>$L_X$</td>
<td>$\log \left( \frac{L_X}{\text{erg s}^{-1}} \right) &lt; 44.0$</td>
<td>69</td>
</tr>
<tr>
<td></td>
<td>$44.0 \leq \log \left( \frac{L_X}{\text{erg s}^{-1}} \right) &lt; 44.5$</td>
<td>99</td>
</tr>
<tr>
<td></td>
<td>$44.5 \leq \log \left( \frac{L_X}{\text{erg s}^{-1}} \right)$</td>
<td>69</td>
</tr>
<tr>
<td>$L_{bol}$</td>
<td>$\log \left( \frac{L_{bol}}{\text{erg s}^{-1}} \right) &lt; 45.8$</td>
<td>80</td>
</tr>
<tr>
<td></td>
<td>$45.8 \leq \log \left( \frac{L_{bol}}{\text{erg s}^{-1}} \right) &lt; 46.3$</td>
<td>77</td>
</tr>
<tr>
<td></td>
<td>$46.3 \leq \log \left( \frac{L_{bol}}{\text{erg s}^{-1}} \right)$</td>
<td>80</td>
</tr>
<tr>
<td>$M_{BH}$</td>
<td>$\log \left( \frac{M_{BH}}{M_{\odot}} \right) &lt; 8.6$</td>
<td>58</td>
</tr>
<tr>
<td></td>
<td>$8.6 \leq \log \left( \frac{M_{BH}}{M_{\odot}} \right) &lt; 9.0$</td>
<td>67</td>
</tr>
<tr>
<td></td>
<td>$9.0 \leq \log \left( \frac{M_{BH}}{M_{\odot}} \right)$</td>
<td>63</td>
</tr>
<tr>
<td>$\lambda_{Edd}$</td>
<td>$\lambda_{Edd} &lt; -1.0$</td>
<td>64</td>
</tr>
<tr>
<td></td>
<td>$-1.0 \leq \lambda_{Edd} &lt; -0.7$</td>
<td>71</td>
</tr>
<tr>
<td></td>
<td>$-0.7 \leq \lambda_{Edd}$</td>
<td>53</td>
</tr>
</tbody>
</table>

$^a$These sources are not included in the main sample considered in Section 4, but each has the same data requirements as the 237 sources which are included.

4.1 X-ray spectral parameters

The X-ray spectral properties of the AGN in this sample were studied in detail in S11. A best-fitting X-ray power-law slope, $\Gamma$, was determined for each and the presence of additional spectral components such as a soft X-ray excess and intrinsic cold absorption were tested for using an F test at 99 per cent significance. Since the X-ray emission from AGN is thought to originate in the very central regions close to the black hole, it provides a direct probe of the accretion process. Here, we investigate whether the properties of this emission have an effect on the multiwavelength emission which is produced further from the central source in the accretion disc and torus.

Average SEDs of sources binned according to their best-fitting X-ray power-law slope are shown in Fig. 6 (top). As expected by definition, the SED shape in the X-ray band is different for each of the subsamples, although the dispersion present in the flatter $\Gamma$ SED is much larger than for the other subsamples. This is due to the presence of four sources with $\Gamma < 0.7$ giving a much larger range of $\Gamma$ values in this subsample. The SED shape at frequencies $\log \nu \sim 13–16$ is remarkably similar and the three SEDs are almost entirely consistent within 1σ (there is some deviation in the IR). This suggests that the multiwavelength emission of the sources has no dependence, or influence, on the shape of the X-ray power-law emission.

Figure 6. Average SEDs of sources binned according to their X-ray spectral properties. The top plot shows variations with the X-ray power-law slope, $\Gamma$, the middle plot compares the SEDs of sources which did, or did not, significantly require a soft X-ray excess component in the original X-ray spectral modelling and the bottom plot compares sources best fit with a simple power-law model to those requiring significant X-ray absorption. In this case the sources used are not included in the original sample of 237 sources, but do have SEDs which are well sampled with the same data requirements. The inset panels plot the median values only.
Fig. 6 (middle) compares the average SED of AGN in which a soft X-ray excess component was significantly detected in their X-ray spectra, to those which did not statistically require the component in addition to a simple power law. In general the two SEDs have similar shapes suggesting the presence of a soft excess component in the X-ray spectrum does not influence the source’s emission at other wavelengths. This is expected, as the results of Scott, Stewart & Mateos (2012) showed that it is merely the X-ray spectral quality which limits the detection of a soft excess and the feature is ubiquitous in this sample of type 1 AGN. The sources are hence from the same overall population regardless of whether the soft excess is significantly detected. We therefore expect their SED shapes to be the same and we continue to include these sources in our analysis. We might have expected to see a slight up-turn in the soft X-ray region of the SED as a signature of the soft X-ray excess. This feature is indeed present in the median of the SED including significantly detected soft excesses, but is masked by the reasonably large dispersion on a relatively low number of sources in the subsample. We plot just the medians of the two SEDs in the inset panel. This up-turn is also visible in the original full sample of 761 sources in which a soft excess was not necessarily significantly detected and can be clearly seen in Fig. 4. This further supports the ubiquity of the soft excess.

The physical origin of the soft excess component is still debated in the literature, but may be related to the intrinsic disc emission (e.g. Done et al. 2012). Unfortunately, in the average SED of sources with a significantly detected soft excess, the BBB, which is tracing the accretion disc, is poorly sampled. This is because the soft excess is easier to detect in lower z sources as it lies in a greater proportion of the XMM–Newton European Photon Imaging Camera’s (EPIC) bandpass (Strüder et al. 2001; Turner et al. 2001) which introduces a strong redshift bias into the subsample. However, the peak of the BBB is sampled and is located at a lower relative flux level (∼1σ) and a higher rest-frame frequency for sources with a significantly detected soft excess.

Fig. 6 (bottom) compares the average SED of all 237 AGN with well-sampled SEDs to one made up of AGN with intrinsic absorption present in their X-ray spectra. Only 12 of such sources are used here as we require the SEDs to include the same number of flux measurements as the full sample. The fluxes which make up the SEDs of the absorbed sources are corrected for Galactic \(N_H\) (in the X-ray fluxes) and Galactic \(A_V\) (in the optical and UV fluxes), but are not corrected for intrinsic absorption in any band. The intrinsic X-ray absorption column densities for these 12 sources are in the range \(N_H = (0.1–9.8) \times 10^{22} \text{ cm}^{-2}\).

Despite the poorly defined shape of the average absorbed SED, which is due to the low number of sources included, clear differences between this and the unabsorbed SED are apparent. As expected, there is a lower level of emission at X-ray frequencies where the absorbing material has the greatest effect with the SEDs being distinct at >1σ at frequencies \(\log \nu \lesssim 17.5\). However, the optical/UV region of the SED does not display signs of similar reddening. This is partly due to the dispersion in the absorbed SED masking the effect, which becomes visible in the inset panel where only the median values of the two SEDs are plotted. As this effect is not large, it may suggest that the presence of gas absorption in the X-ray regime does not necessarily imply that dust reddening in the optical will also be present. This topic is addressed further in Scott et al. (in preparation) by studying the X-ray and optical spectra of the sample in more detail. There appears to be relatively more emission at MIR frequencies, however, we note that due to our plotting method which normalizes individual SEDs by their bolometric luminosity,
Figure 8. Average SEDs of the 237 AGN which have a well-sampled SED (see Section 3 for details). The sources are further subdivided based on the parameters 2–10 keV X-ray luminosity, $L_X$ (top left), bolometric luminosity, $L_{bol}$ (top right), black hole mass, $M_{BH}$ (bottom left), and Eddington ratio, $\lambda_{Edd}$ (bottom right). The median redshift of the sources in each luminosity bin is shown in brackets on the top two figures. In each figure the horizontal error bars indicate the rest-frame frequency at which the peak of the BBB occurs in the median SED, with the 1σ subsample dispersion. The inset panels show enlargements of the median SEDs around the BBB peak and these error bars.

the significantly lower relative emission level at X-ray frequencies will naturally result in an increased emission level in the rest of the SED. Even after taking this effect into consideration the SEDs of absorbed and non-absorbed sources are distinct at $>1\sigma$ at frequencies $\log \nu \leq 13.5$. This may be due to the absorbing material producing extra re-radiated emission.

Intrinsic X-ray absorption is expected to be present in up to 10 per cent of optically classified type 1 AGN (Scott et al. 2012) and we consider such objects to belong to a different subpopulation of objects from their typical, unabsorbed counterparts. This, and the large difference between the absorbed and non-absorbed SEDs justifies the exclusion of the absorbed sources from the subsample of sources considered in our analysis.

4.2 Redshift dependence

Each of the sources in the sample has a spectroscopic redshift measured by SDSS. They cover the range $0.11 \leq z \leq 3.29$, with 95 per cent of sources at $z < 2$, and both the mean and median redshift of the sources is $z \sim 0.9$. Here we investigate the effect of redshift on the SED shape to determine whether an intrinsic, non-evolving type 1 AGN SED exists. There have been previous studies investigating whether individual measures of the SED emission vary with redshift. In particular, there is thought to be no evolution of $\Gamma$ with $z$ (Reeves & Turner 2000; Piccioni et al. 2003; Mateos et al. 2005a,b; Shemmer et al. 2005; Vignali et al. 2005a,b; Shemmer et al. 2005, 2006; Just et al. 2007; Green et al. 2009) and no evolution of $\alpha_{OX}$ with $z$ (Vignali, Brandt & Schneider 2003; Steffen et al. 2006; Just et al. 2007; Green et al. 2009; Young, Elvis & Risaliti 2009; Stalin et al. 2010). This suggests that the emission at X-ray, UV and optical wavelengths is non-evolving, and we should expect to find no shape evolution in the SED at these frequencies.

In higher redshift sources the observed fluxes correspond to higher rest-frame frequencies and hence the average rest-frame SED lies at a slightly different frequency range. This effect is clearly visible in Fig. 7 (top) and is particularly important in the FUV region of the SED, which marks the beginning of the EUV gap. The Lyman continuum edge occurs at a rest-frame frequency of $\log 15.5 (= 13.6 \text{ eV} = 912 \text{ Å})$ and frequencies higher than this are unmeasurable due to absorption by neutral hydrogen in our Galaxy. However, for sources at $z \geq 0.7$, the observed FUV flux has a rest-frame frequency which probes into the EUV gap. Therefore, in the two
average SEDs at higher redshift, some of this unpenetrable region is being sampled. These SEDs show a decrease in the UV, thought to be probing the intrinsic disc emission. In order to determine whether our SEDs are affected by Lyα absorption, we calculate the power-law index, α, where Fν ∝ ν−α over the range 1200–2000 Å for each of the average SEDs. The values are consistent with the value given by Shull, Stevans & Danforth (2012) for unabsorbed sources, suggesting that no significant attenuation is present in our SEDs.

The peak of the BBB occurs at a lower relative emission level in lower redshift sources than for those at high z. The relative emission levels of the low- and high-z SEDs are distinct at greater than their 1σ dispersions from log ν ∼ 14.92 until the cut-off frequency at the edge of the EUV gap, however, the SEDs are consistent within their 2σ dispersions. We quote the median bolometric luminosity for each of the z bins in Fig. 7 (top) as the Lbol − z bias is apparent. It is therefore possible that the differences in the BBB emission observed are a result of the changing luminosities of the sources, rather than on z. This is investigated in Section 4.4. The rest-frame frequency at which the peak of the BBB occurs is also seen to shift to higher frequencies in lower redshift sources as shown by the error bars plotted above the SEDs. However, we note that this shift is only ∼1σ.

A striking difference between the SEDs is the higher relative emission levels at MIR frequencies in the high-z sources. The low- and high-z SEDs become distinct at >1σ at a frequency of log ν = 13.75, but are still consistent within 2σ at the low-frequency end of the SED. This emission is thought to be due to the re-radiation of higher frequency primary emission from the central source, by dust further away.

The average SED made up of the lowest redshift sources shows a feature at a rest-frame frequency of log ν ∼ 14.7. This is due to a number of sources at z = 0.4 (the average for this subsample) having an increased SDSS z-band flux. This is likely due to the broad emission line Hz falling into this photometric band for these sources. This feature is not apparent in the mid-z subsample which has an average redshift of z = 1.0 as Hα falls into the NIR J band and the sources considered are not required to include this flux measurement. Hα falls in between NIR bands for sources in the higher z subsample.

### 4.3 Object class

A benefit of our large sample size is the opportunity to identify reasonable numbers of AGN subtypes within the type 1 classification. These include radio-loud sources which we identify using their radio and optical fluxes, and NLS1s identified by the width of their broad emission lines.

We identify 17 NLS1 through a cross-correlation of the S11 sample with the Zhou et al. (2006) catalogue. This includes 2011 NLS1 sources, identified from SDSS DR3 within the range z ≤ 0.8. A well sampled SED is available for 11 NLS1, the average of which is plotted in Fig. 7 (middle) in blue. This is compared to an average SED of 94 sources which lie within the redshift range covered by the catalogue and are hence confirmed as non-NLS1.

The average SED for the NLS1s shows a significantly steeper X-ray slope than their broad-line counterparts, consistent with literature results (e.g. Grupe et al. 2010; Jin et al. 2012a) and the relative X-ray flux also appears to be lower in the average NLS1 SED. However, the MIR–UV SED shape does not appear to vary between the two types of source, in that their 1σ widths are consistent throughout most of this frequency range. This suggests that the main physical difference between them is in the X-ray emitting corona. This may be a difference in electron temperature or optical depth, since Γ depends on these parameters. Results in the literature do report changes in the SED at lower frequencies. For example, Jin et al. (2012a) find the peak of the BBB to be a more prominent feature in NLS1 with a steeper Γ. This is not apparent in this figure, possibly due to the limited number of NLS1s. However, in Section 4.1, we also found no change in the BBB with variations in Γ when we considered all type 1 AGN.

The radio loudness, R, for each source was determined using the radio flux from FIRST and the optical fluxes from SDSS as described in more detail in S11. A source was defined as radio loud if R > 10 (Kellermann et al. 1989). Fig. 7 (bottom) compares the average SED of RQQ to RLQ. In order to display the radio portions of the SEDs, both the x- and y-axes of this figure have been extended. In the case of the RQQ, the emission shown at radio frequencies represents an upper limit because we only include objects for which there was a significant radio detection by FIRST; there are objects whose radio emission is too low to be significantly detected and we do not include sources with radio upper limits in our analysis.

As expected, the RLQ have greater amounts of radio emission than the RQQ, with the SEDs being distinct at >2σ over the entire radio portion of the SED. The RLQ also have more emission at X-ray frequencies, the SEDs being distinct at 1σ over the frequency range log ν = 17.6–18.4. These observations are consistent with the previous analysis in S11 and with observations in the literature and suggest that the radio and X-ray emission is linked (e.g. Zamorani et al. 1981; Worrall et al. 1987; Brinkmann et al. 2000; Reeves & Turner 2000; Miller et al. 2011; Shang et al. 2011). The emission at both frequencies may be due to the presence of a jet, producing radio photons through synchrotron emission, and X-ray photons from synchrotron self-Compton scattering. The SED also shows a different shape at X-ray frequencies. This is again consistent with the results of S11 in which Γ was flatter in RLQ than RQQ. This may be due to contamination of the X-ray power-law emission by the jet. The SED shape in the MIR–UV region (shown enlarged) is very similar for both the RQQ and RLQ, with the better defined RQQ SED lying almost entirely within the 1σ error boundary of the RLQ SED (the BBB peak is higher and there is more relative IR emission at log ν ∼ 13.7). The RLQ SED has a much larger dispersion due to the low number of sources included, which also masks the inflection point in the NIR.

These results imply that RQQ and RLQ are fundamentally the same objects and hence produce the same broad-band emission, but the presence of a jet gives rise to the additional radio and X-ray emission observed. The similarity of the SEDs with the exception of the radio and X-ray bands has been observed previously (Elvis et al. 1994; Shang et al. 2011).

### 4.4 Physical parameters

In this section we investigate how the average SED shape changes with variations in different physical parameters such as Lx, Lbol, Mbh and λedd. Finding observational correlations between physical parameters can provide constraints for theoretical models of the emission.

Previous studies have investigated the luminosity dependence of emission in individual bands (e.g. X-ray and optical: Lusso et al. 2010; IR: Maiolino et al. 2007) and we therefore expect to see some change in the SED shape with luminosity. Polletta et al. (2007) presented average SEDs of type 1 AGN binned by their 0.5–10 keV luminosity. No significant differences were seen, but this is likely a result of the low numbers of sources included. In Fig. 8 (top left) we show average SEDs produced from 70 to 100 AGN in each
2–10 keV X-ray luminosity bin. It shows that the X-ray contribution to the SED is approximately the same in each subsample, that is they are consistent with each other within their $1\sigma$ errors shown by the width of the plotted SED. However, the median is higher in the highest $L_X$ subsample suggesting a slightly larger X-ray contribution, although this is not statistically significant. This would agree with the requirement of a luminosity-dependent X-ray bolometric correction (e.g. Marconi et al. 2004). The amount of emission contributed from each band within the MIR–UV frequency range does vary between subsamples, although the combined contribution must be approximately the same. The average SED made from low $L_X$ sources has a rather flat shape, whereas the high $L_X$ sources show a higher BBB peak and lower IR emission (the SEDs are distinct at $\sigma_4$ between $14.1–14.4$ and $14.9–15.4$). This suggests that in sources with higher X-ray luminosities, a greater amount of the AGN’s emission comes out in the optical/UV. This is in agreement with the anticorrelation found between $\alpha_{OX}$ and the optical luminosity, $\log L_{2500}^{\lambda}$ implying a non-linear relationship between the optical and X-ray emission (Avni & Tananbaum 1986; Vignali et al. 2003; Strateva et al. 2005; Steffen et al. 2006; Just et al. 2007; Vasudevan & Fabian 2007; Shemmer et al. 2008; Young et al. 2009; Lusso et al. 2010; Staljin et al. 2010). These SEDs show a significant difference at radio frequencies with relatively more radio emission in sources with higher X-ray luminosities, consistent with the results of the RLQ in Section 4.3.

Fig. 8 (top right) shows how the SED shape varies with changes in the bolometric luminosity of the source. The $L_{bol} – z$ bias is apparent in this figure with the highest $L_{bol}$ SED covering higher frequencies due to the higher $z$ sources it includes: the median $z$ of the low $L_{bol}$ SED is 0.36, $\bar{z} = 1.01$ for the mid $L_{bol}$ SED and $\bar{z} = 1.37$ for the high $L_{bol}$ SED. The main difference between the SEDs is the steeper gradient in the higher luminosity SED between the NIR inflection point and the peak of the BBB. This is similar to the behaviour of the SEDs when binned according to $L_X$. As discussed in Section 3, the difference in the NIR may be an indication of some contamination by the host galaxy which is expected to have the largest effect in the $H$ band for sources at $z = 0.5$ (McLeod & Rieke 1995). In the lowest luminosity sources the inflection point appears less pronounced, possibly due to the addition of emission from the host galaxy, whose SED has the opposite shape.

As the SEDs are normalized by their bolometric luminosity, the $y$-axis indicates the relative amount of emission at each frequency. This is similar to the way in which bolometric correction factors would quantify this. In the X-ray band, the amount of emission appears to vary with the bolometric luminosity of the source with X-rays contributing more in the low-luminosity SED and less in the high-luminosity SED. This implies that a luminosity-dependent X-ray correction is required, supporting the results of Marconi et al. (2004). However, the low and high $L_{bol}$ SEDs are only distinct in the X-ray band at $\leq 1\sigma$. The high-luminosity sources also show relatively more emission in the BBB ($\geq 1\sigma$) implying that the bolometric correction factor for these frequencies must also have a luminosity dependence. However, at IR frequencies $\log v \leq 14.4$, the SEDs are almost consistent within their $1\sigma$ dispersions suggesting that within the luminosity range of sources included by our sample, the bolometric correction factor in these bands is constant and is not dependent on the luminosity of the source. This is also shown in Hopkins, Richards & Hernquist (2007).

Virtually determined black hole mass estimates taken from Shen et al. (2008) are available for 188 (79 per cent) of the sources. The average SEDs binned according to this parameter are shown in Fig 8 (bottom left). The three SEDs show a remarkably similar shape at all frequencies (all three are consistent within their $1\sigma$ dispersion), suggesting that the multiwavelength emission from type 1 AGN is largely insensitive to the mass of the accreting black hole. However, the peak of the BBB occurs at a higher relative flux level and lower rest-frame frequency for the SED containing AGN with higher mass black holes. A correlation between $\Gamma$ and $M_\bullet$ has been found in the literature (Porquet et al. 2004; Piconcelli et al. 2005; Kelly et al. 2008; Risaliti, Young & Elvis 2009), but is not apparent in this figure. However, it is generally thought that the underlying driver of this correlation is one with accretion rate (Porquet et al. 2004; Wang, Watari & Mineshige 2004; Bian, Yuan & Zhao 2005; Piconcelli et al. 2005; Shemmer et al. 2006, 2008; Risaliti et al. 2009; Grupe et al. 2010).

We therefore consider whether the SED shape varies with accretion rate for which we use the Eddington ratio, defined here as $\lambda_{Edd} = \log (L_{bol}/L_{Edd})$, as a proxy. We use the bolometric luminosity determined from the SED fitting described in Section 3 and the black hole mass estimates from Shen et al. (2008) to determine the Eddington luminosity. Fig. 8 (bottom right) shows that the X-ray emission is flatter in the SED made up of low Eddington ratio sources, and steeper in the higher Eddington ratio SED. The MIR–UV region is broadly similar for each of the subsamples, however, the gradient between the inflection point and the peak of the BBB is steeper in the higher Eddington ratio SED. This is mostly due to the relatively lower emission in the NIR ($<1\sigma$), but is also partly due to a higher optical/UV peak. An increased disc emission in higher Eddington ratio sources was also observed by Jin, Ward & Done (2012b). This figure also suggests that the peak of the BBB may be shifted to higher frequencies with increasing Eddington ratio, albeit not with high significance ($\sim 2\sigma$).

5 DISCUSSION

In Section 4 we presented average SEDs of different subsamples of type 1 AGN and found their shapes to vary. Such variation suggests that the physical structure or emission mechanisms within the individual AGN may vary, and it is important to understand the physical drivers behind these changes. Some of the more dramatic differences we see are due to the sources belonging to different subpopulations. X-ray absorbed type 1 AGN show a large deficit of emission at optical to X-ray frequencies and an excess of emission at MIR frequencies. As their SEDs are so different to the unabsorbed sources, we regarded them as a separate population of objects and excluded them from the rest of the study. Radio-loud quasars show a very similar SED to radio-quiet sources over the IR–UV frequency range, but show considerable differences at radio and X-ray frequencies, likely related to an additional jet component. NLS1 also have a very similar SED shape to their broad-line counterparts over the majority of frequencies but show large differences in the X-ray regime suggesting different conditions in the X-ray emitting corona. These results suggest that the subpopulations are all fundamentally the same type of object, but have some physical differences which can cause large variations in their SEDs. When we consider changes with underlying physical parameters, we see more subtle changes in the SED shape.

The X-ray emission properties of AGN are critical for the interpretation of the accretion process and it is important to determine how this emission affects the rest of the source. We found that the X-ray spectral parameters appear to have little influence, or dependence, on the emission in the rest of the SED. Therefore the X-ray emission is a poor indicator of the emission properties at other frequencies. We see a wide range in the allowed spectral properties.
at X-ray wavelengths, possibly due to their greater sensitivity to physical changes in the very central regions of the AGN close to the black hole. In contrast, the emission from the accretion disc sitting at larger radii shows very similar spectral properties for all AGN. This suggests that the X-rays, and changes in this emission, do not have any effect on the accretion disc properties.

The BBB, which traces the accretion disc, is one of the major features in the SEDs. In our analysis we have seen subtle changes in both the relative flux level of the peak of this component, and the rest-frame frequency at which this peak occurs. If the accretion disc is assumed to radiate locally as a blackbody, this peak frequency can be used to determine the inner disc temperature. This depends on both the mass of the black hole and the accretion rate (see equation (4)) and for a typical AGN with a $10^5 \, M_\odot$ black hole and $m = 0.1$ is $T_{\text{in}} \approx 200,000 \, \text{K}$ ($\sim 0.02 \, \text{keV}$):

$$T_{\text{in}} \propto \left( \frac{m}{\dot{m}_{\text{Edd}}} \right)^{1/4} \left( \frac{M}{M_\odot} \right)^{-1/4}.$$  

For lower redshift AGN the peak of the BBB lies at a higher rest-frame frequency and a lower relative flux level than for those at higher $z$. This is the same behaviour displayed by AGN which include a significantly detected soft X-ray excess component, as they are generally low-$z$ sources due to the bias involved in the detection of the component. The shift in BBB peak frequency seen between low- and high-redshift SEDs corresponds to a $\sim 10$ per cent decrease in the inner disc temperature ($\Delta T \sim 22,000 \, \text{K}$). This could be due to either higher black hole masses or lower accretion rates in the high-$z$ AGN. The peak frequency of the BBB does not change with luminosity ($L_X$ or $L_{\text{bol}}$), but the relative flux level does change, indicating that the amount the BBB emission contributes to the total luminosity of the source increases with luminosity. The relative flux level of the peak is also higher for AGN with higher $M_{\text{BH}}$ and occurs at a lower rest-frame frequency. We also find that the BBB peak frequency shifts with Eddington ratio, giving lower temperatures in lower accretion rate sources. The peak frequency, expressed here in energy, shifts from $\sim 0.009 \, \text{keV}$ in low accretion rate AGN to $\sim 0.01 \, \text{keV}$ in the mid and high Eddington ratio bins, which show approximately the same peak frequency and flux. We expect the inner disc temperature to depend on both the black hole mass and the accretion rate as indicated by equation (4), but the accretion rate itself also depends on the mass of the black hole. It is therefore unclear whether the main driver of the peak frequency shift is that of the black hole mass or the accretion rate. However, we also observe some slight changes in the X-ray emission in the SEDs binned by Eddington ratio, specifically flatter power-law slopes in lower accretion rate sources. When coupled with the observed shift in the peak frequency of the BBB we can draw analogies between the behaviour observed here in AGN and the different spectral states observed in Galactic black hole binaries (e.g. Belloni 2010). In the high/soft state in which the accretion rate is high ($-1 < \lambda_{\text{Edd}} < -0.3$) and the X-ray power-law slope is steep, the disc is thought to extend close in to the black hole resulting in a hotter inner disc temperature ($T \propto r^{-3/4}$). Conversely in the low/hard state, where the accretion rate is low ($\lambda_{\text{Edd}} < -1$) and the X-ray power law is flat, the inner accretion disc is thought to truncate further out from the black hole, leaving a geometrically thick, optically thin advection-dominated accretion flow and a lower inner disc temperature (Esin, McClintock & Narayan 1997). This scenario is consistent with the results shown by the different average SEDs presented here, in which the lowest Eddington ratio subsample includes objects in the low/soft state, whilst the top two bins fall into the high/soft state.

We include WISE data in our SEDs which samples the MIR region probing dust, allowing us to investigate the physical properties of this material. We see clear differences in the MIR emission of absorbed sources and the SEDs produced from sources binned by their redshift. There is relatively more MIR emission in the higher $z$ sources than the low-$z$ sources, which due to the flux-limited sample may be a luminosity effect instead. However, when we bin the sources according to their bolometric luminosities, no difference is seen. Calderone et al. (2012) fit the MIR emission of a similar sample of AGN with a superposition of two blackbodies with temperatures of 1500 and 300 K, possibly representing the inner (hotter) and outer (cooler) edge of the dusty torus. In Fig. 7 (top; $z$ dependence), we see a possible blackbody peak at a $(\log)$ frequency of 14.1, similar to Calderone et al. (2012). This appears to be the same for each of the three redshift bins. We also see evidence for another blackbody component at lower frequencies, although we are only sampling the tail of the distribution rather than the peak. However, we do see that the peak temperature would be higher in the highest $z$ SED, implying a higher temperature of dust for these sources. If these two temperatures were to correspond to the inner and outer edges of the dusty torus, it is unclear why only one of these temperatures should show a $z$ dependence. We suggest that the two components may instead be sampling different regions of dust. In the case of the absorbed sources, we estimate that $\sim 10$ per cent of $L_{\text{bol}}$ is absorbed in the X-ray and optical region, with $\sim 7$ per cent of this being re-emitted in the MIR. This additional MIR emission corresponds to dust with a temperature of $\sim 1000 \, \text{K}$.

This work has the advantage of studying a large sample of SEDs which include AGN with a wide range of physical and spectral properties. However, the sample was created from the optical SDSS quasar catalogue and the X-ray source catalogue 2XMMi, along with additional archival multiwavelength catalogues which imposes some biases and caveats into the resulting sample. It is biased against the weakest X-ray sources as only AGN with $>75 \, \text{X-ray spectral counts}$ are included, and the sensitivity limit varies across each of the frequencies we sample. However, in this work it is more important to accurately sample the shape of the SED by including as many flux measurements as possible than to have a flux complete sample of objects. We therefore selected a subsample of AGN with detections in as many flux bands as possible. By requiring the inclusion of NIR and UV data in our SEDs we do create a slight bias towards lower redshift and lower luminosity sources, but still cover a wide range in these parameters. We do not include any data at FIR frequencies leading to a large interpolated region between the W4 and radio bands. However, the majority of the emission at these frequencies would be due to starburst activity rather than the AGN (Netzer et al. 2007; Mullaney et al. 2012).

The multiwavelength data we use are from non-contemporaneous observations where in some cases the data were taken many years apart. As AGN are known to be variable, this could mean that some of our SEDs are constructed from data points taken when the intrinsic SED shape of the source was different. Spectral changes seen at optical and X-ray frequencies are more rapid than the variability time-scales in the IR band. However, in this work we focus on investigating variations in average SEDs created from a large number of individual objects which makes any such temporal variations less important.

6 CONCLUSIONS

In this paper we have created broad-band SEDs of a large sample of type 1 AGN using archival data from XMM–Newton (X-ray),
GALEX (UV), SDSS (optical), UKIDSS (NIR), 2MASS (NIR), WISE (MIR) and FIRST (radio). 237 AGN (31 per cent) of the initial sample have well sampled SEDs over a large frequency range from which we created average SEDs, binned according to different properties and physical parameters. We investigated variations in the shape of these SEDs in order to determine how changes in these parameters affect the AGN emission at different frequencies.

We found that the SEDs of type 1 AGN subpopulations do show considerable differences. X-ray absorbed sources show a large deficit in the optical/X-ray regime and an excess at MIR frequencies, consistent with re-emission from the same absorbing material. RLQ are consistent with being the same type of physical source as RQQ, but with an additional jet component which contributes extra X-ray and radio emission from non-thermal processes. NLS1 show significant differences in the spectral shape of their X-ray emission, perhaps related to physical variations in the corona, but the rest of the SED is similar to their broad-line counterparts.

The multiwavelength emission does not appear to have any dependence on the shape of the X-ray spectral emission. We see a wide variety of X-ray spectral slopes, but only a narrow range of IR–UV variations. This indicates that although the accretion processes occurring in the central regions close to the black hole can vary substantially, the emission from the accretion disc at large scales and the torus are generally similar for all AGN. Similarly the presence of a soft excess does not alter the rest of the SED emission. We also found that the X-ray emission contributes a lower amount to the overall emission in AGN with high bolometric luminosities. This explains, and illustrates, the need for a luminosity-dependent X-ray bolometric correction in which the X-ray contribution decreases with increasing $L_{\text{bol}}$. AGN with higher X-ray luminosities also emit a greater amount of their emission at optical/UV frequencies which agrees with the previously known anticorrelation between $\alpha_{\text{OX}}$ and $L_{\text{bol}}$.

We see some shifts in the peak frequency of the BBB which suggest a change in the inner disc temperature. The shift seen between low- and high-$z$ sources is likely to be a consequence of an underlying change in accretion rate or black hole mass. Increased inner disc temperatures in higher accretion rate sources may be suggestive of a change in the accretion disc structure in analogy with spectral states observed in Galactic black hole binaries.

Our SEDs come from type 1 AGN spanning a wide range of parameters. Given this, it is perhaps remarkable that the diversity in the SEDs is relatively small, particularly at frequencies lower than X-rays and higher than radio. Subtle dependencies on a number of physical properties are evident, but there is no apparent single driver for these variations.

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