A deep ROSAT survey – XV. The average QSO spectrum and its evolution

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Abstract

Using a sample of 165 X-ray selected QSOs from seven deep ROSAT fields \( f(0.5-2.0\text{keV}) \gtrsim 4 \times 10^{-15} \text{erg cm}^{-2} \text{s}^{-1} \), we investigate the X-ray spectral properties of an ‘average’ radio-quiet broad-line QSO as a function of redshift. The QSO stacked spectra, in the observer’s 0.1–2 keV band, in five redshift bins over the range 0.1 \( \leq z \leq 3.2 \), apparently harden from an equivalent photon index of \( \Gamma \sim 2.6 \) at \( z = 0.4 \) to \( \Gamma \sim 2.1 \) at \( z = 2.4 \) as seen in other QSO samples. In contrast, the spectra in the 0.5–2 keV band show no significant variation in spectral index with redshift. This suggests the presence of a spectral upturn at low energies (<0.5 keV). Indeed, while at high redshifts (\( z > 1.0 \)) the single power-law model gives an acceptable fit to the data over the full energy band, at lower redshifts the spectra need a second component at low energies, a ‘soft excess’. Inclusion of a simple model for the soft excess, i.e. a blackbody component \( (kT \sim 100 \text{eV}) \), results in a significant improvement to the model fit, and yields power-law slopes of \( \Gamma \sim 1.8–1.9 \), for all redshift bins. This power law is not inconsistent, within the error bars, with those of nearby active galactic nuclei (AGN) in the 2–10 keV band, suggesting that the same intrinsic power-law slope may continue from 10 keV down to below \( 0.5 \) keV. We caution that there is a possibility that the spectral upturn observed may not represent a real physical component, but could be caused by co-adding spectra with a large dispersion in spectral indices. Regardless of the origin of the soft excess, the average QSO spectrum has important consequences for the origin of the X-ray background: the average spectra of a typical, faint, high-redshift QSO are significantly steeper than the spectrum of the X-ray background, extending the spectral paradox into the soft 0.1–2 keV X-ray band.

Key words: galaxies: active – galaxies: evolution – quasars: general – X-rays: galaxies.

1 INTRODUCTION

Following the discovery of X-ray luminous QSOs \( \sim 25 \text{yr ago} \) (Lampton et al. 1972), we remain without a detailed description of the form and emission mechanism of QSO X-ray spectra, despite extensive studies of these objects.

Satellite missions such as Ginga and EXOSAT indicated that the X-ray emission of radio-quiet QSOs (which constitute the vast majority of the QSO population) above \( \sim 2 \text{keV} \) can be well described by a power law with a photon index of \( \Gamma \sim 1.9 \) (Lawson et al. 1992; Williams et al. 1992). However, the sources detected by these experiments, which are the X-ray brightest, typically with \( f_x \gtrsim 1 \times 10^{-12} \text{erg cm}^{-2} \text{s}^{-1} \), nearby \( (z < 0.2) \) QSOs, may not be representative of the class as a whole. Reeves et al. (1997) observed a small number of bright radio-quiet QSOs with ASCA, extending these results to higher redshifts. Recent long-exposure \( (\sim 100 \text{ks}) \) ASCA observations (Georganopoulos et al. 1997) extend the investigation of average QSO X-ray spectra down to even fainter flux limits of \( \sim 5 \times 10^{-14} \text{erg cm}^{-2} \text{s}^{-1} \) in the 2–10 keV band. Although the photon statistics are not sufficient to be conclusive, there is some evidence that the spectral index of these faint QSOs is flat \( (\Gamma = 1.5 \pm 0.2) \).

Observations of the soft X-ray spectrum \( (<2 \text{keV}) \) of radio-quiet, optically selected QSOs made with the Einstein observatory show a steeper spectral index \( (\Gamma > 2) \). This suggests that the QSO...
spectra are concave, i.e. they cannot be represented by a single power law over a broad energy band (e.g. Schwartz & Tucker 1988). This steep soft spectral index could be interpreted as excess emission (soft excess) at energies below ~1 keV, above the extrapolation of the X-ray power-law slope found at higher energies. Such a soft excess is detected in a substantial number of quasars (Masnou et al. 1992; Saxton et al. 1993), and in about 50 per cent of nearby Seyfert-type active galactic nuclei (AGN) (Turner & Pounds 1989). Ciliegi & Macaccaro (1996) examine the 50 per cent of nearby Seyfert-type active galactic nuclei (AGN) quasars (Masnou et al. 1992; Saxton et al. 1993), and in about 10~20 per cent of the extragalactic sources at high redshifts. Schartel et al. (1996a) studied the stacked spectra of a sample of 908 objects from the Large Bright Quasar Survey (LBQS) sample of optically selected QSOs. They find a mean spectral slope of $\Gamma \approx 2.5$ and marginal evidence for a flattening of the spectral index at higher redshifts. Schartel et al. (1996b) analysed the individual spectra of a sample of 55 radio-quiet QSOs from the ROSAT All-Sky Survey. They again find steep spectral indices $\Gamma \approx 2.5$ and no evidence for spectral evolution with redshift. Laor et al. (1997) also derive a steep spectral index $\Gamma \approx 2.72 \pm 0.09$ using a sample of 19 radio-quiet, optically selected QSOs with $z < 0.4$.

The above values for the spectral slope of QSOs constitute the discrepancy known as the spectral paradox (Boldt 1987), in that the most common class of X-ray source has a spectral index significantly steeper than that of the X-ray background (XRB), which has $\Gamma \approx 1.5$ at both hard (Marshall et al. 1980; Gendreau et al. 1995) and soft energies (Georgantopoulos et al. 1996), and so cannot be the major contributor to the XRB flux. A resolution of the spectral paradox could be the evolution of the mean QSO X-ray spectrum with redshift.

Here, we derive the average QSO spectral index using a sample of X-ray-selected QSOs detected in seven fields from our deep ROSAT survey (Shanks et al. 1991; Georgantopoulos et al. 1996). Previous work by Almaini et al. (1996) in five of our fields finds no variation with redshift in the slope of the spectra of QSOs (as determined by analysis of hardness ratios in the 0.5–2.0 keV band) from five deep ROSAT fields. In order to identify the effect of a soft excess (emission significant only at $\approx 0.5$ keV) on the resultant power-law slope in the 0.1–2.0 keV band, we use here the full ROSAT energy band and also perform proper spectral fits to the data. In this paper we include two further deep ROSAT fields in our investigation, creating a sample of 165 QSOs covering a broad redshift range, $0.1 \leq z \leq 3.2$, with a relatively high mean redshift ($\bar{z} \approx 1.5$). We also include two longer exposures (50 ks each) of the QSF1 and QSF3 fields, which, along with the increased range of energies considered, results in photon statistics that are effectively doubled over those in the Almaini et al. work. Preliminary results from this work were presented in Stewart et al. (1994). The goals are (i) to detect and quantify the possible evolution of the QSO spectral index, (ii) to compare the QSO spectra with that of the XRB, and (iii) to examine the possibility for an upturn of the average spectral index in the soft band.

## 2 X-ray Data Selection

We use data taken from deep X-ray observations of seven fields with the ROSAT PSPC (a summary of the observations taken is shown in Table 1). Over 300 sources were detected within the inner ring of the detector, at the $4\sigma$ level, down to a flux of $\approx 4 \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$ (0.5–2.0 keV). After an optical identification programme with the Anglo-Australian Telescope (AAT), 165 QSOs were identified: see Georgantopoulos et al. (1996) for the full details of the identification procedure and Shanks et al. (in preparation) for the catalogue of sources. Redshifts are in the range $0.1 \leq z \leq 3.2$. Fig. 1 shows the distribution.

Data sets used in this work are available from the Leicester Database and Archive Service (LEDAS) ROSAT public data base. We exclude data from periods of high particle background; i.e. when the master veto rate is above $170$ count s$^{-1}$ (Plucinsky et al. 1993) typically ~10 per cent of the data is rejected. Correction of the spectra for vignetting and the point spread function (PSF) were performed with the asterix software package. A background spectrum was accumulated from the region inside the inner ring of the detector, with all sources detected above the $4\sigma$ level masked out and using a circular region with a radius of 90 arcsec.

The search for spectral evolution of an average QSO requires binning the data into sufficient redshift subsamples to detect trends over the redshift range. However, one must strike a balance between the number of redshift bins and the resultant number of objects and photons in each bin. Clearly the number of photons must be adequate to allow for full spectral fitting, also, a low number of sources per bin may result in the spectrum being dominated by one particular source, rather then representing the spectrum of a mean source. Details of the redshift bins used,

![Figure 1. Redshift distribution, $N(z)$, for the QSO sample, with a mean redshift $\bar{z} = 1.44$.](https://academic.oup.com/mnras/article-abstract/314/1/138/1046557/139)
including the total number of background-subtracted photons in each bin, are given in Table 2. In addition to these redshift-segregated spectra, we created a spectrum including data from all 165 QSOs. We note also that the photons were distributed evenly over the fields; thus no one observation or field will dominate the results. One of the two observations of the QSF3 field and one of the two observations of the QSF1 field was made with the PSPC-C instrument, so with these data we use the `pspcc_gain1_256.rsp` matrix. We use the `pspcb_gain2_256.rsp` matrix for all other observations, as they are made after October 1991 with the PSPC-B. Spectral fitting is performed for spectra from each field and instrument simultaneously.

3 SPECTRA AND RESULTS

Initially we considered the energies in the range 0.5–2.0 keV, and fitted a simple power-law plus absorption-column model to the data, for comparison with the results from Almaini et al. (1996). The Galactic \( N_H \) for all our fields (Stark et al. 1992, see Table 1) is reasonably low, with a range of \( \sim 1.2-3.0\times10^{20} \) cm\(^{-2} \) and an exposure-weighted mean of \( N_H \approx 2.0 \times 10^{20} \) cm\(^{-2} \). Hereinafter, unless otherwise stated, for the Galactic \( N_H \) used in model fitting we use the appropriate \( N_H \) for each of the fields included in each of the spectra. The best-fitting power-law index found from the stacked photons from all redshift bins is \( \Gamma = 2.23 \pm 0.07 \) (Table 3), with a \( \chi^2 \) value of 1.07 from 157 degrees of freedom, in excellent agreement with Almaini et al. Errors quoted throughout this paper are 90 per cent errors, calculated on the basis of the conservative assumption that all spectral parameters (including normalization) are interesting.

Following this, we fitted the same model to data from each redshift bin individually, resulting in best-fitting photon indices presented graphically in Fig. 2, and in tabular form in Table 4. A \( \chi^2 \) test shows that this model is formally acceptable in each redshift bin; furthermore, we find a non-evolving spectral slope, consistent, within errors, in each redshift bin, with the value for \( \Gamma \) found when considering data from all redshift bins together. These results are also consistent with the Almaini et al. results for the QSO spectral slope as a function of redshift [see fig. 3b of Almaini et al. (1996)].

We then tested our data over the range 0.1–2.0 keV with the same model. The derived photon indices are shown in the upper panel of Fig. 3, with the \( \chi^2 \) given in the lower panel. For comparison, the best-fitting photon index found for data taken from all QSOs is represented by the dashed line in the upper panel, with the 1σ error shown by the dotted lines. Evolution of the derived power-law photon index is found, in that \( \Gamma_{(0<1.0)} \approx 2.50 \) and \( \Gamma_{(1.0<3.2)} \approx 2.25 \). To establish the significance of this difference in spectral slope, we performed spectral fits on two further spectra, including data from QSOs in the redshift ranges 0.0–1.0 and 1.0–3.2 respectively (for results see Table 3). This difference is significant at over the 8.5σ level. It is, however, easily seen that this model provides an increasingly inadequate description of the data for smaller redshifts, indeed a \( \chi^2 \) test rejects the model fit in the two lower redshift bins to at least the 99.9 per cent level.

The typical shape of a spectrum that rejects this model is shown in Fig. 4, the residuals (lower panel) clearly indicating a systematic difference between the data and the model at energies \( \approx 0.5 \) keV. To determine whether the data requires absorption in excess of the Galactic value, as seen in a small number of AGN (Ciliegi & Maccacaro 1996), we allowed the absorbing column density to be a free parameter in the fit, again performing the fit for both PSPC-B and PSPC-C spectra simultaneously, and with independent column densities. Fig. 5 shows how the best-fitting column density varies with redshift for the PSPC-B spectra (uppermost panel) and the PSPC-C spectra (middle panel), with the dashed line representing the appropriate weighted mean Galactic \( N_H \), and the dotted lines the estimated uncertainty in the mean. The total absorbing column is consistent with the Galactic value in all the redshift bins. Neither inclusion of \( N_H \) as a free parameter nor including an intrinsic warm absorber reduces the \( \chi^2 \) significantly, as determined by an \( F \)-test (Bevington & Robinson 1994), in any of the redshift bins.

| Redshift range | QSOs | Photons 0.1–2.0 keV |
|---------------|------|---------------------|
| 0.0–0.5       | 0.36 | 78                   |
| 0.5–1.0       | 0.78 | 32                   |
| 1.0–1.5       | 1.23 | 54                   |
| 1.5–2.0       | 1.77 | 44                   |
| 2.0–3.2       | 2.42 | 28                   |

| Redshift range | Model: PL 0.0–2.0 keV \( \Gamma \) \( \chi^2 \) \( \nu \) | Model: PL 0.1–2.0 keV \( \Gamma \) \( \chi^2 \) \( \nu \) | Model: PL+BB 0.1–2.0 keV \( \Gamma \) \( \chi^2 \) \( \nu \) |
|---------------|-----------------------------|-----------------------------|-----------------------------|
| 0.1–3.2       | 2.23(10)0.07                | 2.39(10)0.02                | 2.12(23)1.17                |
| 0.1–1.0       | 2.33(10)0.11                | 2.66(10)0.03                | 2.68(16)1.86                |
| 1.0–3.2       | 2.15(10)0.10                | 2.24(10)0.04                | 1.60(16)1.90                |
redshifted blackbody. The derived photon indices and $x$-tried a two-component model consisting of a power law plus a low energies (e.g. Turner and Pounds 1989; Fiore et al. 1994), we results from nearby AGN, which have a spectral upturn towards our QSO sample when fitted with a simple power-law model. Figure 3. Results from fitting a simple power-law model over the energy range 0.1–2.0 keV, with an absorbing column fixed at the Galactic value. The upper panel shows the best-fitting photon indices with 1$\sigma$ errors, the lower panel the reduced $\chi^2$ for each redshift bin. In the upper panel the best-fitting $\Gamma$, from a model fit to stacked data from QSOs in all redshift bins, is shown by a dashed line, with 1$\sigma$ errors given by the dotted lines. Figure 4. Plot of the co-added spectrum from QSOs, at all redshifts, observed with the PSPC-B instrument, with the best-fitting power-law model (see Table 3) shown by the solid line. The data/model ratio is given in the lower panel, which exhibits the systematic discrepancies typical of our QSO sample when fitted with a simple power-law model.

In an attempt to fit the 0.1–2.0 keV spectra, and guided by results from nearby AGN, which have a spectral upturn towards low energies (e.g. Turner and Pounds 1989; Fiore et al. 1994), we tried a two-component model consisting of a power law plus a redshifted blackbody. The derived photon indices and $x$-tried are shown in Fig. 6 and Table 4. We see a significant reduction in the $\chi^2$ caused by the inclusion of this soft excess, even though the model is still formally rejected in the lowest redshift bin. Figure 5. Free-fit absorption, found in the 0.1–2.0 keV band using a power-law plus photoelectric absorption model, plotted against redshift. We show the results from the PSPC-B and PSPC-C spectra in the uppermost and middle panels respectively, with 1$\sigma$ errors. The dashed lines are the mean Galactic values appropriate for each of the spectra, from Stark et al. (1992), with the dotted lines showing the approximate uncertainty in the Stark et al. values. The lower panel gives the reduced $\chi^2$ for each model fit.

Table 4. Details of spectral fitting results in five redshift bins. Errors quoted are at the 90 per cent confidence level.

| Redshift range | Model: PL 0.5–2.0 keV $\Gamma$ | Model: PL 0.1–2.0 keV $\Gamma$ | Model: PL+BB 0.1–2.0 keV $\Gamma$ |
|----------------|--------------------------------|--------------------------------|----------------------------------|
|                | $\chi^2_G$ ($n$)               | $\chi^2_G$ ($n$)               | $\chi^2_G$ ($n$)                 |
| 1 0.0–0.5      | 2.38$^{+0.13}_{-0.12}$ 0.65(58) | 2.53$^{+0.03}_{-0.03}$ 2.23(224) | 1.84$^{+0.16}_{-0.19}$ 1.34(217) |
| 2 0.5–1.0      | 2.02$^{+0.17}_{-0.17}$ 1.35(47) | 2.54$^{+0.05}_{-0.05}$ 1.42(159) | 1.77$^{+0.32}_{-0.31}$ 1.12(149) |
| 3 1.0–1.5      | 2.09$^{+0.18}_{-0.18}$ 0.99(60) | 2.21$^{+0.04}_{-0.05}$ 1.31(180) | 1.57$^{+0.27}_{-0.27}$ 1.05(169) |
| 4 1.5–2.0      | 2.25$^{+0.20}_{-0.20}$ 1.23(45) | 2.14$^{+0.07}_{-0.06}$ 0.99(128) | 2.11$^{+0.18}_{-0.14}$ 0.95(117) |
| 5 2.0–3.2      | 2.18$^{+0.30}_{-0.30}$ 0.89(19) | 2.08$^{+0.10}_{-0.10}$ 1.44(47) | 2.04$^{+0.14}_{-0.15}$ 1.09(38) |

Figure 6. Best-fitting power-law photon indices (along with 1$\sigma$ errors) found over the energies 0.1–2.0 keV, when including a redshifted blackbody soft excess component in the spectral model. The reduced $\chi^2$ for each redshift bin is given in the lower panel. In the upper panel, the dashed line denotes the best-fitting photon index found when fitting a power-law plus blackbody model to data from all the QSOs, with 1$\sigma$ errors shown by the dotted lines.

However, this result is probably not unreasonable, as we have co-added the photons from many sources at slightly different redshifts (and having different physical parameters and geometries); thus a single blackbody model may not provide a perfect description of the data. We find that the power-law slope derived when including a blackbody soft excess is, in each redshift bin, consistent within the 90 per cent errors with $\Gamma \approx 1.8 \pm 0.2$, the.
value found for the entire sample of QSOs together. This value is consistent, within the 90 per cent error bars, with the intrinsic AGN power-law index of $\Gamma \sim 1.9$ (Nandra & Pounds 1994), suggesting that the hard power law continues down to below $\sim 0.5$ keV in the QSO rest frame. The best-fitting temperatures of the blackbody components ($kT \sim 100–200$ eV) are in general agreement with those found for quasars (Rachen, Mannheim & Biermann 1996) and nearby radio-quiet QSOs (Fiore et al. 1994). Modelling the soft excess as a thermal bremsstrahlung, a hot plasma, or an additional power law yields similar $\chi^2$ results over the five redshift bins, and derived power-law indices that, again, are around $\Gamma \sim 1.8$.

While we note that our description of the soft excesses found in the binned spectra as a simple single-temperature blackbody is simply an expedient to obtain a better statistical representation of the data, and as such may not be fully representative of the true spectra of individual objects, or the underlying physical properties, it is of interest to examine the behaviour of the blackbody parameters as a function of redshift bin. In Fig. 7 and Table 5 we present the best-fitting blackbody temperature and the luminosity of the blackbody component as a function of redshift (now fixing the power-law photon index at 2 in order better to constrain the blackbody properties). It is clear that the blackbody temperature, while consistent with measurements for nearby objects of similar luminosity (Fiore et al. 1994) at zero redshift, increases in temperature to higher redshifts, rising from $\sim 100$ eV in the most local bin to of order 200 eV at redshifts $\sim 2$. In contrast, the mean luminosity of the blackbody per object remains approximately constant.

We first ask whether the effect could be some instrumental artefact, as the blackbody temperature in the observer’s frame remains roughly constant. A systematic error in the calibration of the effective area, for example, could cause such an effect. We can rule out this possibility by noting that the fractional contribution from the soft excess relative to the power-law component varies with redshift from bin to bin, while a systematic uncertainty or error in the calibration would give a constant fractional contribution. Another possibility is that the results we obtain are an artefact of our assumption that the spectra of QSOs within a redshift bin can be represented by a single value of $\Gamma$. For example, co-adding a step and a flat spectrum would result in a steep and flat spectrum at low energies and high energies respectively, i.e. a concave spectrum. In principle, deriving the spectra of individual QSOs would circumvent this problem. Fiore et al. (1994) find that a large fraction of the QSOs in their sample (four out of six) reveal a soft excess at low PSPC energies. In contrast, Laor et al. (1997) find that the PSPC spectra of the majority of their LBQS QSOs are consistent with a single power-law to within 30 per cent. Unfortunately, our objects typically are faint and we cannot derive individual spectra. However, as an exercise we have derived individually the spectra of the two brightest QSOs in the QSF3 field. The column density was fixed at the Galactic value $N_H = 1.7 \times 10^{20}$ cm$^{-2}$. For RX J0342.6–4404 ($z = 0.377$) we obtain $\Gamma = 3.18_{-0.08}^{+0.08}$ for a single power-law fit ($\chi^2 = 59.9/51$ degrees of freedom). The addition of a blackbody component (0.06 keV) is significant at the 99 per cent confidence level ($\chi^2 = 51.0/49$ degrees of freedom) with $\Gamma = 2.58_{-0.21}^{+0.25}$. In contrast, RX J0342.0–4403 ($z = 0.635$) can be fitted with a single power law ($\Gamma = 2.9_{-0.10}^{+0.20}$) without the need of an additional component ($\chi^2 = 40.3/38$ degrees of freedom). It is evident that a conclusive answer on the origin of the soft excess cannot be given with the photon statistics currently available. Finally, it is possible that a range of individual QSO spectra could result in artificially induced behaviour that varies with redshift as a result of sampling different energy ranges in each redshift bin. If, for example, QSOs had a range of spectral indices, then sampling at different energy ranges would bias the results, in that when using higher energy bands flatter spectra would be preferentially be sampled, giving rise to an apparent flattening of spectrum with redshift. Such an explanation for the behaviour observed here seems contrived and unlikely given the lack of variation in spectra in bins with redshifts greater than $\sim 1$.

Next, we consider the possible physical origin of the spectral upturn. The soft excesses observed in AGN spectra are often ascribed to the high-energy end of the big blue bump seen in the optical/UV region of the spectrum and thought to originate in the accretion disc (Walter & Fink 1993; Turner & Pounds 1989). The properties of the accretion disc are then dominated by the mass accretion rate and mass of the central black hole. In the simplest models of the emission from the accretion disc, the spectrum is a multi-temperature blackbody with the maximum temperature component coming from the inner disc radii. The behaviour of the soft excess parameters presented here certainly suggests that the emission is more complex than would be expected in a thin accretion disc. The high temperatures found do not fit well with the above models. Moreover, the constant luminosity of the soft excess seen in the ROSAT band while the power-law component increases by a factor of 20–30 is more consistent with up-scattering than with thermal emission from a disc powered by potential energy loss. We note that the constant luminosity of our measured soft excesses is similar to that found by Saxton et al. (1993) for a sample of nearby QSOs. They found that the soft excess parameters presented here certainly suggests that the emission is more complex than would be expected in a thin accretion disc. The high temperatures found do not fit well with the above models. Moreover, the constant luminosity of the soft excess seen in the ROSAT band while the power-law component increases by a factor of 20–30 is more consistent with up-scattering than with thermal emission from a disc powered by potential energy loss. We note that the constant luminosity of our measured soft excesses is similar to that found by Saxton et al. (1993) for a sample of nearby QSOs. They found that the soft excesses presented here certainly suggests that the emission is more complex than would be expected in a thin accretion disc.
excess luminosity saturated above a power-law luminosity of $\sim 10^{44}$ erg s$^{-1}$, the mean luminosity in our lowest redshift bin. They postulated that this was caused by a decreasing temperature of the soft excess. Such an explanation is contradicted by our results, which are more in keeping with an increasing mass accretion rate, rather than black hole mass being the important factor.

Regardless of the origin of the spectral upturn at low energies, the average QSO spectrum has important implications for the origin of the XRB. Boldt (1987) argues that, as the AGN have hard ($2-10$ keV) X-ray spectra, significantly steeper than the spectrum of the XRB in the same band (Marshall et al. 1980), they cannot produce the bulk of the XRB. This spectral paradox appears to extend to the lower ROSAT energies. The XRB in the 0.5–2 keV band also has this flat spectral index, $\Gamma \sim 1.5$ (Georgantopoulos et al. 1996; Vecchi et al. 1999). All previous studies of the QSO spectra in the ROSAT band (e.g. Schartel et al. 1996b; Laor et al. 1997) obtain spectral indices much steeper than the XRB spectrum in the same band. However, these contain mainly bright, low-redshift QSOs. In contrast, our sample contains typical QSOs in the sense that our objects constitute a large fraction (over ~50 per cent at 1 keV) of the XRB and they cover a wide range of redshift and luminosity. Our results clearly show that the soft X-ray-selected QSOs cannot produce the bulk of the soft XRB. Another population with a flat X-ray spectrum is needed at faint fluxes. This population may be associated with AGN obscured in X-ray wavelengths; some examples of this population at low redshift ($z < 0.5$) may already have been identified in deep ROSAT pointings (Schmidt et al. 1998).

4 CONCLUSIONS

We derived the average QSO spectrum and its evolution with redshift, using a sample of 165 QSOs from seven deep ROSAT fields ($f_{\text{det}} > 4 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$). We find strong evidence (>8$\sigma$) for spectral evolution, in that the 0.1–2.0 keV spectra flatten from $\Gamma \sim 2.6$ at low redshifts to $\Gamma \sim 2.1$ at $z \sim 2.4$. At high redshifts a power-law model with Galactic absorption describes the stacked spectra well, with the power-law index in rough agreement with the slope found from the 0.5–2.0 keV spectra. However, for $z < 1.5$ the spectra of the QSOs in the 0.1–2.0 keV band cannot be fitted by a single power law, with Galactic absorption, in contrast to some other ROSAT results for low-redshift QSOs (e.g. Laor et al. 1997). Furthermore, we find that these deviations from a simple power law cannot be modelled by excess $N_H$ absorption along the line of sight. The above suggest the presence of a soft excess below 0.5 keV in the QSO rest frame. Indeed, when we add a blackbody component to model the soft excess, we obtain a significant reduction in the $\chi^2$ for the low-redshift bins. However this model is still rejected in the lowest redshift bin, probably because a single-temperature blackbody cannot represent adequately the co-added soft excess of all QSOs in one bin. The resulting power-law component has a photon index $\Gamma \sim 1.8 \pm 0.2$, and shows no evidence of evolution with redshift. This spectral index is not inconsistent, within the 90 per cent errors, with both the canonical AGN spectral index of $\Gamma \sim 1.7$ observed in the 2–10 keV band and the intrinsic spectral slope of $\Gamma \sim 1.9$, suggesting that the hard X-ray power law may continue well into the ROSAT band, down to below $\sim 0.5$ keV. The soft excess probably evolves with redshift, maintaining a constant luminosity but increasing in temperature, from 100 eV locally to 200 eV at $z \sim 2$. We caution that the blackbody model is simply an expedient to obtain a better statistical representation of the data. It is possible that the soft excess observed may be purely an artefact of the co-addition of spectra with a large range of spectral indices. Regardless of the origin of the soft excess, the average QSO spectrum has important implications for the origin of the XRB. It is shown here that the average spectrum of faint, high-redshift QSOs is much steeper than the spectrum of the XRB in the soft 0.1–2 keV band, extending the spectral paradox to low energies. Future missions such as XMM are expected to bring a breakthrough in the spectral studies of high-redshift, faint QSOs, because of their broad energy coverage and high effective area.

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