Is the soft excess in active galactic nuclei real?

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ABSTRACT

We systematically analyse all publicly available XMM–Newton spectra of radio-quiet PG quasars. The soft X-ray excess in these objects is well modelled by an additional, cool, Compton scattering region. However, the remarkably constant temperature derived for this component over the whole sample requires a puzzling fine tuning of the parameters. Instead, we propose that the soft excess is an artifact of strong, relativistically smeared, partially ionized absorption. The strong jump in opacity at $\sim$0.7 keV from O VII, O VIII and iron can lead to an apparent soft excess below this energy, which is trivially constant since it depends on atomic processes. This can have a dramatic effect on the derived spectrum, which has implications for fitting the relativistic smearing of the reflected iron line emission from the disc.

Key words: accretion, accretion discs – atomic processes – X-rays: galaxies.

1 INTRODUCTION

The broad-band optical/UV/X-ray spectra of active galactic nuclei (AGN) consist of at least two distinct components. The big blue bump, observed in the optical/UV band, is commonly associated with emission from the optically thick accretion disc, while the approximately power-law X-ray tail seen to much higher energies with emission from the optically thick accretion disc, while the bump, observed in the optical/UV band, is commonly associated (AGN) consist of at least two distinct components. The big blue bump, observed in the optical/UV band, is commonly associated with emission from the optically thick accretion disc, while the approximately power-law X-ray tail seen to much higher energies with emission from the optically thick accretion disc, while the bump, observed in the optical/UV band, is commonly associated (AGN) 

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2 DATA REDUCTION

We use the bright quasar sample (Boroson & Green 1992) as a starting point, as these objects (mainly radio-quiet quasars) are selected by their strong blue/UV continuum flux, i.e. have a strong accretion disc component. These are all well studied, so have known (and fairly small) $E(B-V)$ values, together with good bolometric...
3 SPECTRAL FITTING AND RESULTS

We fit each spectrum with a model consisting of two Comptonization continua. The hot component produces the power-law spectrum, while the cool one creates the soft excess. We use XSPEC (Zdziarski, Johnson & Magdziarz 1996a) to describe the shape of these spectra. This is based on an approximate solution of the Kompaneets (1956) equation, and is parameterized by the asymptotic photon spectral index and electron temperature. We assume that the seed photons for both Compton scattering regions come from a disc blackbody of temperature $T_{\text{disc}} = 10^6\,\text{eV}$, which is far outside the $0.3-10\,\text{keV}$ energy band so has no effect on the observed spectral shape. We fix the temperature of the hot component at $100\,\text{keV}$, as its high-energy cutoff is not seen below $10\,\text{keV}$ so the temperature cannot be constrained by the data. The cool component temperature is well constrained, but its spectral index (or equivalently, optical depth) is not, so we fix this at $\Gamma_{\text{soft}} = 2.0$. This intrinsic spectrum is absorbed by column $N_H$, which we allow to vary freely.

The soft excess is statistically significant in all the spectra. The smallest change in $\chi^2$ (for PG 0157+001) is 26 for two extra degrees of freedom compared to the fits without a cool component, giving an $F$-test significance level of $\sim 10^{-6}$. The statistical significance of the soft excess is not necessarily proportional to its strength as the signal-to-noise ratio varies from spectrum to spectrum.

Fig. 1(a) shows the characteristics of the soft excess for each object, plotting temperature against strength of the soft excess, $R_{\text{exc}}$, measured by the ratio of unabsorbed $0.3-2\,\text{keV}$ flux in the cool and hot components. The highest excesses of $R_{\text{exc}} = 4.7$ and 17 are in PG 1211+143 and PG 1404+226, respectively, though the spectrum of the latter has poor signal-to-noise ratio. Other sources have $R_{\text{exc}} \lesssim 1$. We use the condition $R_{\text{exc}} = 0.5$ to divide our sample crudely into objects with strong and weak excess, denoted by filled and open symbols respectively in Fig. 1.

The most striking property of the soft excess is its constancy in temperature. It is distributed in a very narrow range of values between 0.1 and 0.2 keV (Fig. 1a), with tendency to concentrate close to 0.1 keV for sources with large $R_{\text{exc}}$. The mean temperature is $(kT_{\text{soft}}) = 0.12\,\text{keV}$ and variance $\sigma_T = 0.02\,\text{keV}$. Even more interesting is the independence of $T_{\text{soft}}$ on the black hole mass (Fig. 1b). The maximum temperature of the standard Shakura–Sunyaev disc is $T_{\text{disc}} \propto M^{-1/4}(L_{\text{Edd}}/L_{\text{Edd}})^{1/4}$, so we can estimate it from the values given in Table 1. Applying a spectral hardening factor of 1.8 (Shimura & Takahara 1995) we find that the expected disc temperature should be between $\sim 3$ and $\sim 70\,\text{eV}$. This is a rough estimate only, as masses and luminosities are uncertain, as is the fraction of the total luminosity released in the disc. Nevertheless, two things are clear (see Fig. 1c). First, the observed soft excess temperatures of $\sim 0.1\,\text{keV}$ are too high to be direct disc emission. Secondly, the range of variation in $T_{\text{soft}}$ (about a factor 2) is much smaller than the range of disc temperatures (about factor 20). Thirdly, there is no correlation between $T_{\text{disc}}$ and $T_{\text{soft}}$.

The hot component, represented here by Comptonization of the disc photons, is simply a power law in the $0.3-10\,\text{keV}$ band, since the seed photons are well below and the high-energy rollover is well above the observed energy band. Its photon spectral index, $\Gamma$, varies between $\sim 1.5$ and $\sim 2.5$. There is a weak positive correlation between $\Gamma_{\text{soft}}$ and luminosity $L_{\text{Edd}}$ (see Fig. 1e), though unlike the X-ray binaries, there are bright sources ($L/L_{\text{Edd}} > 0.1$) with hard spectra ($\Gamma < 2$). In particular, PG 1211+143 has $\Gamma \approx 1.75$ near Eddington luminosity. There is no obvious correlation between the soft excess temperature and $\Gamma$ (Fig. 1f).

The model generally gives a good fit to the spectra, with reduced $\chi^2/\nu = 1.3$ for most of the data. However, in a few of the highest signal-to-noise ratio spectra there are clear narrow residual features from absorption which are not modelled by our continuum fits. These are most noticeable for PG 1211+143, where $\chi^2/\nu = 2.0$. Detailed studies of its XMM–Newton spectrum has revealed the presence of complex ionized absorption (Pounds et al. 2003). Adding multiple absorbers, together with ionized reflection from

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Table 1. List of PG quasars analysed here. Mass and luminosity were taken from Boroson (2002).
the accretion disc, improves the fit ($\chi^2/\nu = 1.36$) but only weakly affects the underlying continuum. In particular, the strength and temperature of the soft excess remain very similar.

4 THE NATURE OF THE SOFT EXCESS

Comptonization of the accretion disc spectrum can successfully fit the shape of the soft X-ray excess below $\sim 2$ keV in all these Seyfert 1/radio-quiet quasars. However, the temperature of this putative Comptonizing region remains remarkably constant at $0.1 \sim 1/r$ radio-quiet quasars. However, the temperature of this putative Comptonizing region remains remarkably constant at $0.1 \sim 1/r$

Thus the two Comptonizing regions have to be spatially separate and independent.

This constancy of soft spectral shape is even more puzzling when compared to GBH, which show a wide variety of spectral shapes for 0.1 < $L_\text{Edd} < 1$ (e.g. Done & Gierliński 2003). If the accretion properties simply scale up with the black hole mass, we should see a similar variety in AGN, yet we do not. The soft-state spectra of GBH can be modelled by Comptonization on two electron distributions: the cooler thermal and the hotter power law (e.g. Gierliński & Done 2003; Zdziarski et al. 2001). The thermal electrons create a soft ‘hump’ above the power law, but their derived moderate optical depth is much smaller than $\tau \sim 50$, required here. This gives rise to a much smoother and broader shape than the observed soft excess in e.g. PG 1211+143.

5 ALTERNATIVE SOLUTIONS

The universality of the soft excess shape has been noticed before (e.g. Walter & Fink 1993; Czerny et al. 2003). It seems to be much simpler to explain if it is set by some characteristic, physical energy
of the system, such as given by atomic transitions. One obvious feature in the soft energy band is the strong jump in opacity associated with lines and edges of ionized O VII, O VIII and iron at ~0.7 keV. This could have an impact either through absorption or through reflection.

The reflection probability depends on the balance between electron scattering and photoelectric absorption opacity, so the decrease in opacity below ~0.7 keV causes a strong increase in the reflected fraction below this energy for an ionized disc. Czerny & Zycki (1994) showed that such ionized reflection from a disc could fit the moderate resolution ROSAT data on the soft excess in some AGNs, though they required a fairly high reflected fraction, with \( \Omega / 2\pi \sim 2 \). Higher resolution data from XMM–Newton show no obvious spectral features at ~0.7 keV, so if atomic features are responsible for the soft excess then they must be strongly smeared by high velocities and/or gravitational redshifts (Ross, Fabian & Ballantyne 2002; Fiore, Matt & Nicastro 1997). Inner disc, ionized reflected spectra can fit the strong soft excesses seen in the XMM–Newton spectrum of 1H 0707–495 and MCG–6–30–15 (Fabian et al. 2002; Ballantyne, Vaughan & Fabian 2003), although the models require a puzzling range of ionization states, and a geometry in which the direct emission from the hard X-ray source is hidden.

Here we propose instead that the soft excess arises from relativistically smeared absorption, where the characteristic atomic spectral features are again masked by high velocities. Physically, this absorption could arise from a differentially rotating, outflowing disc wind (Murray & Chiang 1997). The complex velocity structure of such a wind is beyond the scope of this Letter, but we roughly model it by a Gaussian velocity dispersion with width \( \sigma / c \sim 0.2 \) convolved with XSTAR (Bautista & Kallman 2001) model of the ionized absorption column. This smeared absorption produces a smooth ‘hole’ in the spectrum which results in an apparent soft excess at low energies, and hardens the spectrum at higher energies (see Fig. 2).

Using this complex absorption, we can fit the spectrum of PG 1211+143 with a single Comptonized continuum, without requiring an additional cool Comptonized component to model the soft excess. Including the additional narrow absorption components and reflection from the disc \( \Omega / 2\pi \sim 1 \) gives a slightly worse fit than with the two-component model, with \( \chi^2 / \nu = 1.65 \). However, the residuals are concentrated at ~0.6 keV, consistent with emission from O VII/O VIII in the wind, or perhaps indicating the inadequacies of a Gaussian velocity profile. Apart from these details, the overall continuum shape is well matched by this model. We leave detailed analysis of this and other sources for future work.

Fig. 3 shows a comparison of the deconvolved and unabsorbed spectra of PG 1211+143 for the two models of the soft excess. The model with a separate Comptonization component (Fig. 3a) has a strong soft excess, with a hard spectrum at high energies \( \Gamma \sim 1.8 \). By contrast, for the smeared, ionized absorber, there is only a single continuum component, with much steeper spectral index \( \Gamma \sim 2.7 \). This is much closer to what is seen in the high-luminosity GBH systems, which generally have \( \Gamma > 2 \).

![Figure 2](image_url). An illustration of the ionized absorption model creating the soft excess. The upper line is an underlying power law with spectral index \( \Gamma = 2.7 \). The grey line (red in the online version) shows the moderate absorption features predicted by an XSTAR model with \( N_H = 33 \times 10^{22} \) cm\(^{-2} \) and \( \xi = 460 \) erg cm s\(^{-1} \) (best-fitting parameters to PG 1211+143). The curved thick line shows the this absorbed continuum convolved with a Gaussian of \( \sigma / E = 0.28 \). This figure can be seen in colour in the on-line version of this article on Synergy.

![Figure 3](image_url). Unabsorbed model components together with unfolded and unabsorbed data from PG 1211+143. Open stars represent OM data, crosses (black, blue and red in the online version) represent EPIC MOS, PN and (non-simultaneous) RXTE PCA data, respectively. The dotted curve (red in the online version) represents the disc spectrum. (a) The model with two Comptonized components and ionized reflection. In this model the soft excess comes from Comptonization in warm optically thick plasma (dashed curve, green in the online version). (b) The model with complex ionized, relativistically smeared absorption, which is not seen here as this is unabsorbed model. Instead, the intrinsic spectrum is very different and does not require any additional component to explain the soft excess. In this interpretation the soft excess is due solely to complex absorption. This figure can be seen in colour in the on-line version of this article on Synergy.

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6 CONCLUSIONS

The soft X-ray excess in radio-quiet quasars can be modelled by including a second, cool Comptonizing component. However, the observed range in its temperature is very small, despite large changes in black hole mass, luminosity and 2–10 keV X-ray spectral index across the sample. This requires some fine tuning of the parameters, and strongly contrasts with the analogous soft-state GBH, with large diversity of the X-ray spectral shape over a comparable range in $L/L_{\text{Edd}}$.

Instead, we propose that the soft excess is an artifact of ionized absorption in a wind from the inner disc. The strong jump in opacity at $\sim$0.7 keV seen from O vii, O viii and iron in moderately ionized material can give an apparent soft excess whose energy is fixed by atomic physics, so trivially is constant across a wide range of objects. If this absorber is associated with an accretion disc wind then its complex velocity structure (differentially rotating and outflowing) gives rise to substantial broadening which masks the sharp atomic features, leaving a smooth continuum. In PG 1211+143 we show that such models can fit the data without requiring a separate soft excess. This can dramatically change the inferred intrinsic spectral slope, which has obvious implications for the robustness of the derived parameters for the broad iron line from the disc. The much softer intrinsic spectrum is now consistent with the soft continua seen from high-luminosity GBH. It also means that these two models for the origin of the soft excess can be unambiguously tested with high signal-to-noise ratio, broad bandpass (0.1–50 keV) data, such as will be obtained by ASTRO-E2.

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REFERENCES


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