What is the origin of the soft excess in active galactic nuclei?

Małgorzata A. Sobolewska* and Chris Done*
Department of Physics, University of Durham, South Road, Durham DH1 3LE

Accepted 2006 September 28. Received 2006 September 26; in original form 2006 September 5

ABSTRACT
We investigate the nature of the soft excess below 1 keV observed in active galactic nuclei. We use the XMM–Newton data of the low-redshift, optically bright quasar, PG 1211+143, and we compare it with the narrow-line Seyfert 1 galaxy, 1H 0707−495, which has one of the strongest soft excesses seen. We test various ideas for the origin of the soft X-ray excess, including a separate spectral component (for example, low-temperature Comptonized emission), a reflection-dominated model, or a complex absorption model. All three can give good fits to the data, and χ²-fitting criteria are not sufficient to discriminate among them. Instead, we favour the complex absorption model on the grounds that it requires less extreme parameters. In particular, the geometry appears to be more physically plausible as the reflected component in the smeared absorption model is no longer dominant, and relativistic distortions, while still clearly present, are not tremendously larger than expected for a disc around a Schwarzschild black hole.

Key words: accretion, accretion discs – atomic processes – galaxies: active – galaxies: individual: PG 1211+143 – galaxies: individual: 1H 0707−495 – X-rays: galaxies.

1 INTRODUCTION

The X-ray spectra of active galactic nuclei (AGN) and quasars have long been known to often contain a ‘soft excess’ component at energies below ~1 keV (e.g. Turner & Pounds 1988). This rises rather smoothly above the extrapolation of the power-law continuum seen in the 2–10 keV band, and seems to connect on to the peak of the UV accretion disc spectrum (Zheng et al. 2001; Czerny et al. 2003). This shape is suggestive of low-temperature, high optical depth Comptonization of the inner accretion disc, in addition to the high-temperature, low optical depth Comptonization required to produce the high-energy power law (e.g. Page et al. 2004a). However, the temperature of this additional component seems remarkably constant in high mass-accretion rate objects (L/L_{Edd} > 0.1), despite a large range in black hole mass and hence inferred accretion disc temperature (Czerny et al. 2003; Gierliński & Done 2004, hereafter GD04; Crummy et al. 2006). The nature of this soft excess becomes even more puzzling when compared to the spectra of Galactic black hole (GBH) binary systems. These can indeed show a low-temperature, high optical depth Comptonized component in addition to the disc and high-energy power-law spectrum (in the very high state). However, while it is initially tempting to identify this as the GBH counterpart of the soft excess seen in AGN (Page et al. 2004b; Murashima et al. 2005), the parameters required are rather different, most obviously in the fact that the temperature of this component is variable in the GBH (Kubota, Makishima & Ebisawa 2001; Kubota & Done 2004).

AGN with the largest soft excesses, generally narrow-line Seyfert 1 galaxies (NLS1; Boroson 2002), also often show a strong deficit at ~7 keV which again has no obvious identification (Boller et al. 2002; Fabian et al. 2002, 2004, 2005; Tanaka, Boller & Gallo 2005). These objects are often highly luminous, close to the Eddington limit, yet their underlying high-energy 2–10 keV spectrum can appear to be rather hard (e.g. GD04; Crummy et al. 2006). All Galactic black holes at L/L_{Edd} ~ 0.5–1 have intrinsically soft power law Comptonized emission (e.g. Remillard & McClintock 2006), though occasional super-Eddington source spectra can be harder (e.g. V404 Cyg: Zyci, Done & Smith 1999).

The constancy of temperature for the soft excess emission could plausibly point to an origin in atomic processes. In particular, there is an abrupt increase in opacity in partially ionized material between ~0.7 and 3 keV due to O VII/O VIII and Fe L transitions which can produce a large increase in reflected or transmitted flux below 0.7 keV, making the apparent soft X-ray excess. The corresponding rise in reflected or transmitted flux above 2–3 keV could also artificially harden the high-energy spectrum, while the same material might also have strong iron features, giving a simultaneous explanation of the 7-keV deficit.

By contrast, models where the soft excess is a separate continuum component require some other explanation for the origin of the iron features and hard spectra, such as partial covering of the source by cold absorbing material (Boller et al. 2002; Tanaka et al. 2004). However, the neutral iron edge at 7.1 keV in these models is not big enough to fit the strongest observed features unless iron
is very overabundant, at least five to seven times the solar value (Gallo et al. 2004; Tanaka et al. 2004; Gallo 2006). More generally, such models seem contrived as the iron features and hard spectra appear to be correlated with the soft excess, pointing to a common origin for the hard and soft spectral complexity (Boller et al. 2003; Reeves, Porquet & Turner 2004; Tanaka et al. 2005). This connection is strongly supported by spectral variability. The rms spectra from these objects typically show more variability in the 0.7–3 keV range than at higher or lower energies (e.g. Gallo et al. 2004; Ponti et al. 2004, 2006). The spectrum below 0.7 keV, which is dominated by the soft excess, typically has the same variability as the spectrum above 3 keV, showing that they are almost certainly linked to the same component. The amplified variability in the 0.7–3 keV region is compelling evidence for an atomic origin for the spectral complexity, as it is exactly over this energy range that the atomic features dominate (Gierliński & Done 2006), but both reflection and absorption can match the variability spectra seen (Gierliński & Done 2006; Ponti et al. 2006).

One obvious problem with the atomic models is that they predict strong, sharp atomic features from the partially ionized material. Such characteristic narrow absorption lines and sharp edges are seen in AGN (warm absorbers) but these can be easily isolated using high spectral resolution data (see e.g. Blustin et al. 2005 and references therein), and a strong smooth soft excess remains. Large velocity smearing is the only way to keep an atomic origin of the soft excess. If at least some of the material is moving at moderately relativistic speeds, the characteristic line/edge features become strongly broadened into a quasi-continuum. Such speeds naturally arise only close to the black hole, so the atomic models predict that the soft excess is formed in regions of strong gravity, irrespective of whether it arises from partially ionized reflection or absorption. However, it is important to distinguish between a reflection or absorption origin for the soft excess, as they give very different geometries and have different implications for our understanding of the X-ray source. In reflection, the partially ionized material is optically thick and out of our line of sight. The accretion disc is the obvious identification but in order to produce the strongest soft excesses a reflection model requires that the intrinsic continuum is strongly suppressed, perhaps by the disc fragmenting or by extreme lightheading (Fabian et al. 2002, 2004, 2005; Miniutti & Fabian 2004). The velocity structure should be Keplerian, and the large inferred smearing implies a very small inner disc radius, and hence extreme Kerr space–time and/or extremely centrally concentrated emissivity (e.g. Miniutti & Fabian 2004). By contrast, in an absorption origin, the partially ionized material is optically thin, and seen in our line of sight. This implies that it is some sort of wind from the disc, so its velocity structure is not well defined, and cannot easily give constraints on the space–time (GD04; Chevallier et al. 2006; Schurch & Done 2006).

The structure of this paper is as follows. In Section 2, we try to distinguish between the reflection and absorption models for the soft excess. We calculate the strength of the soft excess in both models, showing that the largest observed soft excesses can be produced in the absorption model by simply changing the column of material in the line of sight. In Section 3 we explicitly compare reflection and absorption models by fitting data from PG 1211+143 and 1H 0707–495, representative of the largest soft excesses seen in quasars and NLS1s, respectively. Both models give comparably good fits to the data in terms of $\chi^2$ criteria, as does the more phenomenological model of a separate soft component. Statistics cannot discriminate between them, and depending on $\chi^2$ alone may be somewhat misleading as there are systematic uncertainties in the models (such as range of ionization states present) which probably dominate the residuals.

How then can we distinguish between them? The XMM–Newton data is fairly high signal-to-noise ratio, moderate spectral resolution and fairly broad bandpass (0.3–10 keV), yet neither energy nor variability spectra can clearly discriminate between these models. In Section 4, we suggest that simultaneous data at higher energies may be able to break these spectral model degeneracies. We also review the physical plausibility of the models, which leads us to favour the smeared absorption as the origin of the soft excess.

2 COMPARISON OF REFLECTION AND ABSORPTION MODELS FOR THE SOFT EXCESS

We use the results of GD04 to determine the range of soft excess strengths which are required by the data. They defined $R_s$ as the ratio of unabsorbed 0.3–2 keV fluxes in the soft excess and power-law continuum components, respectively. However, the data need to be fitted in order to use such parametrization. An alternative measure of the size of soft X-ray excess, which does not require spectral fitting, is to assume that the spectrum is a power law with single photon index $\Gamma$ but with a step in normalization at 0.7 keV, i.e. $f(E) = A E^{-\Gamma + 1}$ for $E > 0.7$ keV, and $f(E) = S A E^{-\Gamma + 1}$ for $E < 0.7$ keV.

The ratio $S$ of the spectrum at soft energies to that expected from an extrapolation of the higher energy power law is often plotted in the literature (e.g. Porquet et al. 2004), and relates rather simply to the soft excess parametrization of GD04 by $R_s = a(\Gamma)(S - 1) + 1$ where $a(\Gamma) = (0.7^{2-\Gamma} - 0.3^{2-\Gamma})/(2^{2-\Gamma} - 0.3^{2-\Gamma}) = 0.3$–0.6 for $\Gamma = 1.5$–2.5. Thus with this parametrization we can use the objects with ratio plots in the literature as well as data from the sample of GD04. These range from 2 to 3 for the majority of the PG quasars (GD04; Porquet et al. 2004) to >10 for some NLS1s (Boller et al. 2002, 2003; Reeves et al. 2004).

In reflection models, the size of the soft X-ray excess will be set by the solid angle subtended by the reflecting material, and its ionization state. We use ionized reflection spectra of Ross & Fabian (2005) publicly available as ATABLE models in XSPEC. We fix the inclination at 30°, and smear the model by relativistic effects so that the line features do not dominate (we fix the reflector emissivity at 3, and its inner and outer radius at 1.24R_g, i.e. extreme Kerr, and 400R_g, respectively).

Fig. 1(a) shows how the spectral ratio $S$ (evaluated at 0.5 keV) depends on the ionization parameter of the reflector for the maximum ‘normal’ reflection amount of $\Omega/2\pi = 1$. First, it is apparent that partial ionization is required in order to have the soft excess. The strong jump in opacity due to the transition from the oxygen K and iron L shell is only present when these species are present, which requires ($2.5 \leq \log \xi \leq 3.5$). Second, the strength of this soft excess is rather limited. Allowing for super solar iron abundance does not change this conclusion (see Fig. 1a) as it is set by the solid angle of the reflector. Even in the limit of perfectly ionized reflection below 0.7 keV and no reflection at 3 keV, this sets a maximum $S \sim 1 + \Omega/2\pi < 2$ for ‘normal’ reflected emission with $\Omega/2\pi < 1$.

The majority of soft excesses seen from the PG quasars do indeed have $S \lesssim 2–3$ (GD04; Porquet et al. 2004), but the largest soft excess seen require that the spectrum is dominated by the reflected emission rather than the intrinsic continuum (Fig. 1b). This could be done in a geometry in which the disc fragments, or from lightbending distorting the illumination pattern of an initially isotropic source (Fabian et al. 2002, 2004; Miniutti & Fabian 2004). However, if the lightbending interpretation is correct, this predicts a correlation
between the solid angle (reflection dominance of the spectrum) and the amount of smearing as stronger lightbending also focuses the illumination more strongly on to the inner disc. Such a correlation is not seen in the data (Crummy et al. 2006).

Absorption models also require a range of ionization parameter as again they are dependent on the strong opacity jump produced by oxygen K/iron L transitions. To quantify the soft excess strength in the smeared absorption model we assume that the absorber has a Gaussian velocity distribution with $\sigma = 0.2 c$ modifying an intrinsic power-law continuum with photon index of $\Gamma = 2$. The soft excess is then defined as the ratio of the absorption model to extrapolation of a power-law fit to the 3–8 keV spectrum at 0.5 keV, and its strength as a function of ionization parameter is shown in Fig. 2. The soft excess disappears for $\xi \lesssim 2$ as the neutral material absorbs all the soft X-ray emission, and for $\xi \gtrsim 4$ where the column is completely ionized and transparent at all energies. However, the soft excess at $\xi \sim 3$ is now strong enough to match the largest seen. (Note the increase in y-axis range of this figure compared to the reflection plots, and the log scale.) Changing the column changes the size of soft excess, as shown in Fig. 2.

Both the reflection and absorption models require a ‘fine-tuned’ ionization parameter, such that oxygen is partially ionized. This may be explained in the absorption models by the ionization instability, which results from X-ray illumination of material in some sort of pressure balance (Chevallier et al. 2006). However, there is no obvious way to do this in reflection models. The ionization instability in a disc reduces the extent of the partially ionized zone (Nayakshin, Kazanas & Kallman 1999), yet to produce a soft excess from reflection requires that the partially ionized zone has to dominate over the entire photosphere of the disc. It is very difficult for a hydrostatic disc to produce the soft excess (Done & Nayakshin, in preparation). Even without the response of the disc to the irradiating flux, X-ray illumination of a standard Shakura–Sunyaev disc gives an ionization parameter

$$\xi(r) = \frac{L_X}{n(r)(H^2 + R^2)} = 2 \times 10^{11} f m \alpha^{-1.5} (h^2 + r^2)^{-1} c_3^{-1} \text{erg cm s}^{-1},$$

where disc density $n(r) = 2.4 \times 10^{19} a^{-1} m^{-2} m_9^{-1} r^{-1} c_3^{-3} \text{cm}^{-3}$ is taken from Laor & Netzer (1989). $\alpha$ is the viscosity parameter, $m = L/L_{\text{Edd}}$, $L_{\text{Edd}} = 1.3 \times 10^{37} m_9$ erg s$^{-1}$, $m_9 = M_9/(10^9 M_\odot)$, $L_X = \bar{f}L$, so that $f$ is the fraction of the luminosity which goes into hard X-rays, $c_3$ is a relativistic correction, and all the distances are expressed in terms of gravitational radius, $R_g = 1.5 \times 10^{16} m_9$, i.e. $R = r R_g = h R_g$. A similar relation is given by Ross & Fabian (1993). This can give the required value of $\xi \sim 10^{-2.3}$ erg cm s$^{-1}$, but is very dependent on the parameters, changing particularly rapidly with $m$. An alternative prescription for the viscosity, where the heating goes as the geometric mean of the gas and radiation pressure (which may be more physically realistic: Merloni 2003), results in a denser disc and hence a lower ionization parameter of

$$\xi(r) = 8 \times 10^{6} f m^{2.11} m_9^{-0.12} a^{0.88} (h^2 + r^2)^{-1} r^{-0.33} c_3^{-1} \text{erg cm s}^{-1},$$

where $c_3$ is a relativistic correction. This is less strongly dependent on parameters, but both require some method of ‘fine-tuning’ the source height relative to $m$ in order to produce the observed narrow range in ionization parameter.

### 3 Spectral Fitting

The theoretical considerations in the previous section favour an absorption origin for the soft excess as it can reproduce the observed range of soft excess strengths without extreme geometries, and the required ‘fine-tuning’ of the ionization parameter may have an explanation in terms of ionization instability. However, given the model uncertainties, observations may be a better way to distinguish between reflection and absorption as the origin of the soft excess.
We use XMM–Newton data from two representative objects with large soft excesses, the low-redshift (z = 0.085) quasar, PG 1211+143, and the NLS1 galaxy 1H 0707−495 (z = 0.0411). PG 1211+143 is one of the extensively studied objects from Palomar-Green Bright Quasars Survey and was selected based on its optical brightness suggesting super-Eddington accretion rate (Boroson 2002, GD04). 1H 0707−495 is less luminous than PG 1211−143, but it shows one of the strongest soft excesses seen. Both objects show a drop of the flux at 7 keV, which is especially dramatic in the case of 1H 0707−495 (Boller et al. 2002). Their spectra are accretion disc dominated which suggests that they are counterparts of X-ray binaries in the high/soft state (Janiuk, Czerny & Madejski 2001).

We use the Epic PN data, extracted from the data base using standard techniques (see GD04). We fit these data in the 0.3−10 keV energy band using XSPEC to explicitly compare the models for the soft excess.

First, we set up a baseline model where the soft excess is a separate component. We use the COMPPT code of Titarchuk (1994) to describe the soft excess as Comptonization of disc photons (assumed to be at fixed $T_{pp} = 10$ eV) on electrons of temperature $kT_e$, and the optical depth, $\tau$ (Model 1). The soft excess shape generally cannot easily constrain these two parameters separately, so we fixed $\tau = 50$. The hard X-ray tail was modelled by a power law (with photon index $\Gamma$ and normalization) together with its reflection from the accretion disc. We use the publicly available models of Ballantyne, Iwasawa & Fabian (2001), which were then relativistically smeared using the Laor (1991) kernel. This reflection is characterized by the ionization parameter $\xi$, and its normalization, while the smearing parameters are the inner and outer radii of the reflecting disc, together with its inclination (fixed at 30°). We fix the emissivity at 3, which results in rather small value of the outer radius of the reflector. Conversely, fixing the outer radius at (say) 400$_e$ would result in an emissivity greater than 3.

This baseline model is then modified to describe different potential origins for the soft excess. In a reflection origin (Model 2) we replace the COMPPT component (which had two free parameters, namely electron temperature and normalization) with another relativistically smeared reflector (four additional parameters: ionization, normalization, inner and outer radii), while in Model 3 we replace it with the relativistically smeared absorption (the SWIND model of Gierliński & Done 2006) which has three additional parameters: ionization, column and Gaussian velocity smearing, $\sigma$.

All models were additionally modified by the cold Galactic absorption (the WABS model with column densities fixed at 2.7 × 10$^{20}$ and 5.8 × 10$^{20}$ cm$^{-2}$ for PG 1211+143 and 1H 0707−495, respectively), cold absorption at the redshift of the source (the ZWABS model with $z = 0.085$ and 0.0411 for PG 1211+143 and 1H 0707−495, respectively) and warm absorption accounting for the narrow features in the spectra, modelled with the XSTAR code (Bautista & Kallman 2001). We use the most recent XSTAR table models which are publicly available (grid 25) computed for turbulent velocity of 200 km s$^{-1}$ and valid for wide range of ionization parameter and column density ($1 < \log \xi < 5$, $21 < \log N_H < 24$). Hence, the only thing that differentiates the models is the description of the origin of the soft excess.

The spectral decomposition implied by each model is shown in Figs 3 and 4 for PG 1211+143 and 1H 0707−495, respectively. The high-resolution data have been rebinned for clarity of the plots. The detailed model parameters are given in Tables 1−4. These show that

---

1. SWIND model is available from http://heasarc.gsfc.nasa.gov/docs/xanadu/xspec/models/swind1.html
Figure 3. Modelling the soft excess in PG 1211+143. Solid curve: the best-fitting spectra. (a) Model 1 – a low-temperature Comptonization (green/dotted curve), power law (blue/short-dashed curve) and ionized reflection (magenta/long-dashed curve). (b) Model 2 – two reflectors (magenta/dotted and cyan/long-dashed curves) with different column densities and ionization states, located at different radii. (c) Model 3 – a power law (blue/short-dashed curve) subject to relativistically smeared absorption and reflection (magenta/long dashed). (d) Model 4 – same as Model 3 but with the intrinsic power law modified by the addition of a line with P Cygni profile modelling the iron feature. All four models are additionally affected by Galactic absorption, cold absorption at the redshift of the sources and two warm absorbers (see the text).

In the absorption model. By definition this cannot produce sharp features. None the less, sharp features can be produced by a wind with strong velocity shear. P Cygni profiles are an obvious example of this. Done et al. (2006) show that the 7-keV feature in these data from 1H 0707−495 can be fit using a P Cygni profile from emission/absorption/scattering of the He- or H-like resonance iron Kα line at 6.7 or 7.0 keV, respectively. We extend the smeared absorption model by including a P Cygni profile to model the ∼7 keV feature (Model 4: two additional free parameters being the absorption optical depth of the line and its rest energy). Thus, the incident power law is not only affected by the smeared absorption but also has a P Cygni line as in Done et al. (2006).

In Model 4 applying the P Cygni profile to the ∼7 keV feature results in a much improved fit around the iron feature. The inferred line rest-frame line energy of 6.85–7.14 keV, which is consistent with either He- or H-like iron. The fits give $v_\infty/c = 0.5^{+0.2}_{-0.1}$ and $0.5^{+0.0}_{-0.1}$ for PG 1211+143 and 1H 0707−495, correspondingly. The resonance absorption line optical depth in PG 1211+143 is relatively low, $\tau = 0.23^{+0.10}_{-0.06}$, and in 1H 0707−495 it is higher and yields $\tau = 2.0^{+0.9}_{-1.1}$. As in Model 3, the parameters of the remaining reflector are much less extreme than for the reflection model of the soft excess (Model 2). In fact, the deconvolved spectra in Figs 3(d) and 4(d) show that this reflector contributes mainly to producing soft X-ray lines rather than the iron feature, indicating that the reflection...
What is the origin of the soft excess in AGN?

Figure 4. Modelling the soft excess in 1H 0707−495. (a), (b), (c) and (d) as in Fig. 3. (a) Model 1 in 1H 0707−495 does not require intrinsic power law.

Table 1. Best-fitting parameters of Model 1 to PG 1211+143 and 1H 0707−495 data. Plasma optical depth was fixed at τ = 50, emissivity at 3 and inclination at 30°. No intrinsic power-law emission is seen in the model for 1H 0707−495.

<table>
<thead>
<tr>
<th></th>
<th>$kT_e$ (keV)</th>
<th>$\Gamma$</th>
<th>$\log \xi$</th>
<th>$R_i$</th>
<th>$R_f$</th>
<th>$\Omega/2\pi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PG</td>
<td>0.136 ± 0.003</td>
<td>2.02+0.03</td>
<td>2.58+0.04</td>
<td>4.5+0.7</td>
<td>8.7+1.3</td>
<td>4.12 ± 0.49</td>
</tr>
<tr>
<td>1H</td>
<td>0.122 ± 0.002</td>
<td>1.81+0.04</td>
<td>3.00+0.02</td>
<td>3.0+1.0</td>
<td>7.4+4.5</td>
<td>$\infty$</td>
</tr>
</tbody>
</table>

parameters may be further distorted if there is also emission from the wind (see e.g. Schurch & Done 2006).

Table 5 contains parameters of the warm absorbers modifying the continua such as column density, logarithm of the ionization parameter and redshift of the warm absorbers. We find that including the second warm absorber significantly improves the fits in all cases. The last column in Table 5 contains the column density of the cold absorption at the redshifts of the source. It is comparable with the Galactic cold absorption for all models except Model 2 and Model 4 (1H 0707−495 case) for which only the upper limit can be given.

The best-fitting values of $\chi^2$ and number of degrees of freedom are given in Table 6. In PG 1211+143, the worst fit is obtained with the reflection-dominated model. The smeared absorption model is statistically significantly better than the model with low-temperature Comptonization ($F$-test probability of chance improvement $5 \times 10^{-8}$). Modelling the iron feature with a P Cygni profile further improves the fit ($F$-test probability $10^{-5}$). In 1H 0707−495, the smeared absorption model fits worse than either reflection-dominated model or the model with additional
Table 2. Best-fitting parameters of Model 2 to PG 1211+143 and 1H 0707−495 data. Missing upper (lower) limit indicates that the parameter reached its upper (lower) boundary allowed in the fit. Emissivity was fixed at 3 and inclination at 30° and the iron abundance was twice the solar value. The fits are reflection dominated, so $\Omega/2\pi = \infty$.

<table>
<thead>
<tr>
<th>$\Gamma$</th>
<th>$\log \xi_1$</th>
<th>$R_{f1}$</th>
<th>$R_{f2}$</th>
<th>$\log \xi_2$</th>
<th>$R_{f3}$</th>
<th>$R_{f4}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PG</td>
<td>2.127$^{+0.006}_{-0.005}$</td>
<td>3.13 ± 0.01</td>
<td>3.26$^{+0.10}_{-0.06}$</td>
<td>1.88 ± 0.02</td>
<td>22$^{+3}_{-8}$</td>
<td>33$^{+8}_{-4}$</td>
</tr>
<tr>
<td>1H</td>
<td>2.592$^{+0.009}_{-0.013}$</td>
<td>4.00 ± 0.04</td>
<td>4.4$^{+1.4}_{-1.5}$</td>
<td>1.5$^{+0.2}_{-0.2}$</td>
<td>1.89$^{+0.44}_{-0.65}$</td>
<td>20$^{+16}_{-8}$</td>
</tr>
</tbody>
</table>

Table 3. Best-fitting parameters of Model 3 to PG 1211+143 and 1H 0707−495 data. An asterisk indicates that the upper (lower) limit allowed was reached with $\Delta \chi^2 < 2.71$. Emissivity was fixed at 3 and inclination at 30°.

<table>
<thead>
<tr>
<th>$\Gamma$</th>
<th>$N_H$ ($\times 10^{22}$ cm$^{-2}$)</th>
<th>$\log \xi_1$</th>
<th>$\sigma$</th>
<th>$E$ (keV)</th>
<th>$v_{\infty}/c$</th>
<th>$\tau$</th>
<th>$\log \xi_2$</th>
<th>$R_{f1}$</th>
<th>$R_{f2}$</th>
<th>$\Omega/2\pi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PG</td>
<td>2.34$^{+0.03}_{-0.05}$</td>
<td>5.3$^{+0.8}_{-0.8}$</td>
<td>2.43$^{+0.04}_{-0.06}$</td>
<td>0.10 ± 0.01</td>
<td>4.8 ± 0.7</td>
<td>12$^{+6}_{-3}$</td>
<td>1.67 ± 0.47</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1H</td>
<td>2.994$^{+0.006}_{-0.034}$</td>
<td>41$^{+9}_{-13}$</td>
<td>2.89$^{+0.06}_{-0.08}$</td>
<td>0.36$^{+0.09}_{-0.07}$</td>
<td>2.748 ± 0.001</td>
<td>32$^{+0.3}_{-2.0}$</td>
<td>33.8 ± 0.5</td>
<td>1.59 ± 0.83</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4. Best-fitting parameters of Model 4 to PG 1211+143 and 1H 0707−495 data. An asterisk indicates that the upper (lower) limit allowed was reached with $\Delta \chi^2 < 2.71$. Emissivity was fixed at 3 and inclination at 30°.

<table>
<thead>
<tr>
<th>$\Gamma$</th>
<th>$N_H$ ($\times 10^{22}$ cm$^{-2}$)</th>
<th>$\log \xi_1$</th>
<th>$\sigma$</th>
<th>$E$ (keV)</th>
<th>$v_{\infty}/c$</th>
<th>$\tau$</th>
<th>$\log \xi_2$</th>
<th>$R_{f1}$</th>
<th>$R_{f2}$</th>
<th>$\Omega/2\pi$</th>
</tr>
</thead>
<tbody>
<tr>
<td>PG</td>
<td>2.29$^{+0.07}_{-0.05}$</td>
<td>5.0$^{+1.1}_{-0.6}$</td>
<td>2.43$^{+0.06}_{-0.05}$</td>
<td>0.09 ± 0.01</td>
<td>6.58$^{+0.08}_{-0.10}$</td>
<td>0.5 ± 0.2</td>
<td>2.43$^{+0.19}_{-0.09}$</td>
<td>4.8 ± 0.7</td>
<td>12$^{+6}_{-3}$</td>
<td>1.95 ± 0.65</td>
</tr>
<tr>
<td>1H</td>
<td>2.90$^{+0.07}_{-0.19}$</td>
<td>48$^{+3}_{-11}$</td>
<td>2.93$^{+0.05}_{-0.19}$</td>
<td>0.43$^{+0.07}_{-0.06}$</td>
<td>6.58 ± 0.17</td>
<td>0.5 ± 0.1</td>
<td>2.0$^{+0.10}_{-0.11}$</td>
<td>3.12 ± 0.08</td>
<td>60$^{+11}_{-16}$</td>
<td>66$^{+5}_{-2}$</td>
</tr>
</tbody>
</table>

Table 5. Best-fitting parameters for warm absorbers (with $v_{\infty} = 200$ km s$^{-1}$) and cold absorption at the redshift of PG 1211+143 and 1H 0707−495. Missing upper (lower) limit indicates that the parameter reached its upper (lower) boundary allowed in the fit. An asterisk indicates that the upper (lower) limit allowed was reached with $\Delta \chi^2 < 2.71$. Emissivity was fixed at 3 and inclination at 30°.

<table>
<thead>
<tr>
<th>$N_{HI}$ (cm$^{-2}$)</th>
<th>$\log \xi_1$</th>
<th>$z_1$</th>
<th>$N_{HI}$ (cm$^{-2}$)</th>
<th>$\log \xi_2$</th>
<th>$z_2$</th>
<th>$N_{HI}$ (cm$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PG</td>
<td>3.2$^{+1.5}_{-0.6}$</td>
<td>2.79 ± 0.03</td>
<td>$-0.878^{+0.004}_{-0.001}$</td>
<td>6.6$^{+3.7}_{-2.3}$</td>
<td>$10^{19}$</td>
<td></td>
</tr>
<tr>
<td>1H</td>
<td>3.7$^{+1.0}_{-0.9}$</td>
<td>2.89 ± 0.07</td>
<td>$-0.059^{+0.002}_{-0.002}$</td>
<td>1.8$^{+0.6}_{-1.1}$</td>
<td>$10^{20}$</td>
<td></td>
</tr>
</tbody>
</table>

Table 6. The $\chi^2$ values and degrees of freedom in spectral fits to the PG 1211+143 and 1H 0707−495 data.

<table>
<thead>
<tr>
<th>Model 1</th>
<th>Model 2</th>
<th>Model 3</th>
<th>Model 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi^2$ (d.o.f.)</td>
<td>$\chi^2$ (d.o.f.)</td>
<td>$\chi^2$ (d.o.f.)</td>
<td>$\chi^2$ (d.o.f.)</td>
</tr>
<tr>
<td>PG</td>
<td>994 (940)</td>
<td>1012 (939)</td>
<td>963 (939)</td>
</tr>
<tr>
<td>1H</td>
<td>296 (286)</td>
<td>291 (284)</td>
<td>314 (284)</td>
</tr>
</tbody>
</table>

Comptonization. However, including the P Cygni line in a fit improves it dramatically, giving the best overall fit. The $F$-test probability of chance improvement in Model 4 as compared to Models 1 and 2 is of the order of $10^{-4}$.

However, $\chi^2$ criterion alone cannot uniquely distinguish between the three kinds of models as there are many model uncertainties that can contribute to $\chi^2$, e.g. in both the reflection and absorption scenarios we expect an (unknown) range of ionization states to be present. Hence, direct comparison of $\chi^2$ can be misleading when the models are known to be incomplete. Both reflection and absorption models give adequate fits to the data, and rather subtle changes in goodness of fit are not a reliable guide as to which model best describes the soft excess.

A potential possibility to observationally differentiate between the reflection and absorption models may be measuring the high-energy flux with future missions. Based on the interpolation of the best-fitting models we found that the absorption model predicts the 10–30 keV flux at the level of only 50–60 per cent that of
the reflection-dominated model. Fig. 5 shows the predicted model continua (i.e. continua not affected by the warm absorption) in the considered energy band. None the less, we caution that in the most extreme cases, such as that of 1H 0707−495, the inferred wind becomes optically thick to electron scattering (see also Done et al. 2006). The spectrum should then be very messy, with continuum reflection from the wind, as well as absorption and emission from atomic features. This may wash out the expected differences at high energies. Objects with large, rather than extreme, soft excesses (such as PG 1211+143 where the wind is still optically thin) may be better to test its origin.

4 DISCUSSION AND CONCLUSIONS

We tried to determine the origin of the soft excess seen in AGN by fitting 0.3–10 keV XMM–Newton spectra of two representative objects with all currently proposed models, namely a separate continuum, reflection and absorption. All these give comparably good fits to the overall continuum given the model uncertainties (such as range of ionization states). Here, we review the physical plausibility of each model to help distinguish between them.

A separate soft excess component involves an emission from an unknown physical process, with unknown ‘fine-tuning’ mechanism fixing its typical energy. Moreover, this model cannot simultaneously explain the 7-keV feature, nor is it easy to imagine how this can produce the spectral dependence of the variability, where the rms spectra typically peak in 0.7–3 keV band (though it is possible to arrange: Page et al. 2004b). By contrast, both reflection and absorption scenarios are much more plausible, as they give a physical reason for the fixed energy of the soft excess, can reproduce the structure around iron K and give apparently hard spectra in the 2–10 keV band. Thus, an absorption origin seems favoured in terms of physical plausibility, though we note that reflection from the disc should also contribute to the spectrum at some level (Chevallier et al. 2006). Higher energy observations soon to be available from Suzaku may provide a more sensitive test for objects with the soft excess/iron feature not so large as to require an optically thick wind.

ACKNOWLEDGMENTS

This work is based on observations obtained with XMM–Newton, an ESA science mission with instruments and contributions directly funded by ESA Member States and the USA (NASA). This research has made extensive use of NASA’s Astrophysics Data System Abstract Service. CD acknowledges financial support through PPARC Senior fellowship. MS and CD thank Marek Gierliński and Nick Schurch for useful discussions.

REFERENCES


Figure 5. Extrapolation of best-fitting model continua to the 10–30 keV range. The models give different predictions on the 10–30 keV flux, with the reflection-dominated model (magenta/long-dashed curve) producing the highest flux and the smeared absorption model (blue/solid curve) producing the lowest flux. The model with low-temperature Comptonization (green/short-dashed curve) predicts intermediate 10–30 keV flux.