A physical model of the broadband continuum of AGN and its implications for the UV/X relation and optical variability

Aya Kubota\textsuperscript{1,2,*} and Chris Done\textsuperscript{1}

\textsuperscript{1} Department of Physics, University of Durham, South Road, Durham, DH1 3LE, UK
\textsuperscript{2} Department of Electronic Information Systems, Shibaura Institute of Technology, 307 Fukasaku, Minuma-ku, Saitama-shi, Saitama 337-8570, Japan

Accepted XXX. Received YYY; in original form ZZZ

ABSTRACT

We develop a new spectral model for the broadband spectral energy distribution of active galactic nuclei. This includes an outer standard disc, an inner warm Comptonising region to produce the soft X-ray excess and a hot corona. For the first time, we tie these together into a physically based geometry as well as energetically by assuming Novikov-Thorne emissivity. This defines a size scale for the hard X-ray corona from the radius where the remaining accretion energy down to the black hole can power the observed X-ray emission. The data show that the average hard X-ray luminosity is remarkably constant in Eddington units, at $0.02 L_{\text{Edd}}$ for all bolometric luminosities, so the radial size scale required for gravity to power the corona decreases with increasing Eddington fraction. The hard X-ray spectral index is set self consistently from the ratio of this coronal luminosity to intercepted seed photon luminosity from the disc. This matches the observed correlation of steeper spectral index with increasing Eddington ratio. The model fits the overall spectra of representative, low intrinsic absorption objects: NGC 5548, Mrk 509 and PG1115+407, with Eddington ratios of 0.03, 0.1 and 0.3, as well as reproducing the observed tight UV/X relation of quasars. We also include the reprocessed emission produced by the hot inner flow illuminating the warm Comptonisation and standard disc regions and show that this predicts a decreasing amount of optical variability with Eddington ratio, as observed, though additional processes may also be important to explain all of the observed optical variability.

Key words: black hole physics – galaxies: Seyfert – accretion, accretion discs

1 INTRODUCTION

Active Galactic Nuclei (AGN) are powered by mass accreting onto a supermassive black hole (SMBH). The well known Shakura & Sunyaev (1973, hereafter SS73) disc model makes very simple predictions for this emission if it is emitted locally and thermalises to a blackbody. The disc temperature increases inwards (modulo a stress-free inner boundary condition at the innermost stable circular orbit, $R_{\text{ISCO}}$), so the total spectrum is the sum over all radii of these different temperature components (multi-colour disc blackbody; e.g., Mitsuda et al. 1984). However, the observed spectral energy distribution (SED) of AGN are much more complex than this predicts. There is a ubiquitous tail at X-ray energies, as well as an unexpected upturn below 1 keV, termed the ’soft X-ray excess’.

The hard X-ray tail indicates that some part of the accretion energy is not dissipated in the optically thick disc (where it would thermalise) but is instead released on an optically thin region (e.g., Elvis et al. 1994). The resulting Comptonised spectrum from 1–100 keV indicates that this region has electron temperature $kT_e \sim 40–100$ keV and optical depth $\tau \sim 1–2$ (Lubiński et al. 2016; Fabian et al. 2015).

The origin of the ‘soft X-ray excess’ is not well understood. It can be fit by a second Comptonisation region with very different parameters from the coronal emission, one where the electrons are warm, $kT_e \sim 0.1– 0.3$ keV and optically thick $\tau \sim 15–25$ (e.g., Czerny et al. 2003; Gierliński & Done 2004b; Porquet et al. 2004). Alternatively, it could be produced by reprocessing/reflection of the coronal emission on the very inner disc, where extremely
strong relativistic effects smear out the expected strong line emission from ionised material (Crummy et al. 2006). The fastest soft X-ray variability is correlated with, and lags behind, the hard X-ray variability, so some fraction of the soft X-ray excess must be produced from reprocessing/reflection of the corona flux (e.g., Fabian et al. 2013). However, recent results have shown that the majority of the soft excess does not arise from reflection (Mehdipour et al. 2011, 2015; Noda et al. 2013; Matt et al. 2014; Boisson, Ricci, & Paltani 2016; Porquet et al. 2018), favouring the warm Comptonisation model.

The warm Comptonisation scenario also helps to explain another puzzling component of the broadband AGN SED, namely a ubiquitous downturn seen in the UV, at energies far below those expected for the peak disc temperature (e.g., Zheng et al. 1997; Davis, Woo, & Blaes 2007). A warm Comptonisation spectrum can extend across the absorption gap, connecting the UV downturn and the soft X-ray upturn with a single component (Elvis et al. 1994; Laor et al. 1997; Richards et al. 2006). This carries a dominant fraction of the luminosity in the SED of AGN at lower Eddington ratio, $L_{bol}/L_{Edd}$ (Jin et al. 2012a,b), again arguing against a purely reprocessing/reflection origin, though some contribution could be present (e.g., Lawrence 2012). The SED of high $L_{bol}/L_{Edd}$ are instead dominated by disk emission, which can extend into the soft X-ray bandpass for the lowest mass, Narrow Line Seyfert-1 (NLS1) galaxies, but these still have a small fraction of their bolometric power emitted in a soft X-ray excess component (Jin et al. 2012a,b; Done et al. 2012; Jin et al. 2013; Matzeu et al. 2017).

Neither of the Comptonisation components are well understood. However the warm Comptonisation region is especially problematic as, unlike the corona, it does not have a clear counterpart in the much lower mass black hole binary systems (BHB). These often show spectra at $L_{bol}/L_{Edd} \approx 0.1-0.2$ which are dominated by the thermal accretion disc emission, with only a small tail to higher energies from a hot Comptonising corona (e.g., Kubota, Makishima, & Ebisawa 2001; Gierliński & Done 2004a; Steiner et al. 2009)

One obvious break in scaling between BHB and AGN is that the SMBHs have discs which peak in the UV rather than X-ray temperature range. The UV is a region in which atomic physics is extremely important whereas plasma physics dominates in BHB. Nonetheless, the best models of the accretion disc structure including UV opacities (Hubeny et al. 2001) find that the spectra are fairly well described by a sum of modified blackbody components (with atomic features superimposed), similar to BHB spectra (Davis & Hubeny 2006). The addition of UV opacity within the disc alone then may not be enough to explain the soft X-ray excess (though it does also depend on the heating profile within the disc); instead it may be connected to the ability of UV line opacity to launch winds from AGN discs (e.g., Proga, Stone, & Kallman 2000; Laor & Davis 2011) and/or the huge change in opacity connected to Hydrogen ionisation which may be able to change the entire disc structure away from steady state models (Hameury, Viallet, & Lasota 2009).

Constraining the shape of the warm comptonisation component is not easy as it spans the 0.01–1 keV range where interstellar absorption from our own Galaxy obscures our view. Spectral fitting becomes especially degenerate when trying to simultaneously constrain this component along with the hotter coronal component and any residual emission from an outer standard disc (e.g., Jin et al. 2009). Instead, Done et al. (2012) (hereafter D12) assumed that the emission is ultimately powered by energy release from gravity, with the same form as for the thin disc, but that the dissipation mechanism is only blackbody for radii $R > R_{\text{corona}}$. Inwards of this, they assumed that the flow instead emits the accretion energy as a warm or hot Comptonisation component. These energy conserving models (OPTXAGNF: D12) give an additional physical constraint on the components, and more importantly, highlight the fundamental parameters of mass and mass accretion rate (for any assumed spin) in setting the overall SED (Jin et al. 2012a,b; Ezhikode et al. 2017). These models reveal a systematic change in the SED which can be modeled by a decrease in $R_{\text{corona}}/R_{\text{G}}$ (where $R_{\text{G}} = GM/c^2$) correlated with an increase in the hot Comptonisation power law spectra index as $L_{bol}/L_{Edd}$ increases (Jin et al. 2012a,b; Ezhikode et al. 2017; see also Shenmer et al. 2006, 2008 and Vasudevan & Fabian 2007, 2009 for the hard X-ray spectral index).

In this paper, we develop a new model which addresses the underlying physics of these changes, where we assume that the flow is completely radially stratified, emitting as a standard disc blackbody from $R_{\text{out}}$ to $R_{\text{warm}}$, as warm Comptonisation from $R_{\text{warm}}$ to $R_{\text{hot}}$ and then makes a transition to the hard X-ray emitting hot Comptonisation component from $R_{\text{hot}}$ to $R_{\text{ISCO}}$. The warm Comptonisation component is optically thick, so we associate this with material in the disc. Nonetheless, the energy does not thermalise to even a modified blackbody, perhaps indicating that significant dissipation takes place within the vertical structure of the disc, rather than being predominantly released in the midplane (e.g., Davis et al. 2005). At a radius below $R_{\text{hot}}$, the energy is emitted in the hot Comptonisation component. This has much lower optical depth, so it is not the disc itself. It could either be a corona above the inner disc, or the disc could truncate, so that the hot material fills the inner region close to the black hole. We show that the observed steepening of the 2–10 keV spectral index with increasing $L_{bol}/L_{Edd}$ can be most easily explained with a true truncation.

We describe the model structure in section 2, and apply it to observed broadband spectra of individual AGN in section 3 and use these data to set some of the model parameters, so that we can predict the entire AGN SED as a function of only mass and mass accretion rate (for a given black hole spin) in section 4. In section 5, we show that these models reproduce the observed tight relationship between the UV and X-ray emission in Quasars (Lusso & Risaliti 2017) as well as predict a decrease in the fraction of reprocessed optical variability with increasing $L_{bol}/L_{Edd}$ as predicted. Thus, this AGN SED model succeeds in describing multiple disparate observational trends, which gives confidence that the assumed geometry captures most major aspects of the source behaviour.

2 OVERALL DISC MODEL

We follow D12 and assume a radial emissivity like Novikov-Thorne (hereafter NT), defining the flux per unit area at
a radius $R$ on the disc as $F_{\text{NT}}(R) = \sigma B_{\text{NT}}(T_{\text{NT}})(R)$, where $T_{\text{NT}}(R)$ is the effective temperature at this radius. Converting to dimensionless units, with $r = R/R_\text{g}, \dot{m} = M/M_\text{edd}$ and $L_\text{edd} = \eta M_\text{edd} c^2$ gives $F_{\text{NT}} \propto (\dot{m}/M)^{\gamma-3}$ for $r >> 6$. Here $\gamma$ is a spin dependent efficiency factor, assumed fixed at 0.057 for a non-spinning black hole throughout this paper.

2.1 Standard Disc and warm Comptonisation region

In the standard disc region we assume that the NT emission thermalises locally either to give a blackbody $B_r(T_{\text{NT}})$ at the local blackbody temperature, defined from $F_{\text{NT}}(R) = \sigma T_{\text{NT}}^4(R)$, or that electron scattering within the disc distorts this into a modified disc blackbody spectrum. This can be approximated as a colour temperature corrected blackbody, $B_r(f_{\text{corr}}(T)/f_{\text{corr}}$), where $f_{\text{corr}}$ depends on the importance of electron scattering compared to true absorption processes, which itself depends on disc temperature, especially close to Hydrogen ionisation at ~ $10^4$ K. There are few free electrons below this temperature, so electron scattering is not important, and $f_{\text{corr}} \sim 1$, whereas above this temperature there are multiple free electrons so $f_{\text{corr}} > 1$. This effectively shifts the peak of the blackbody over by a factor $f_{\text{corr}}$, and reduces its norm by a factor $f_{\text{corr}}^4$ so this gives a shift to higher energy and decrease in normalisation in the disc spectra from each annulus which onsets at around the hydrogen ionisation energy. Thus the standard disc with this colour temperature correction always has less UV emission (shortwards of ~ $10^{15}$ Hz $\approx 20000\text{ Å}$) than predicted from simple models with $f_{\text{corr}} = 1$ (D12). Figure 1 shows a comparison of the standard disc (geometry I) with $f_{\text{corr}} = 1$ (red solid) to that where $f_{\text{corr}}(T_{\text{NT}})$ is derived from an analytic treatment of the vertical structure of the disc (red dashed line, see also Davis & Hubeny 2006, D12). This clearly shows how the outer disc emission is identical, while the inner disc emission is shifted to higher temperatures/lower luminosities.

In general, the UV data do indeed show a downturn, but this is stronger than predicted by the effect of a changing $f_{\text{corr}}$. Davis, Woo, & Blaes (2007) show that the observed AGN spectra have redder UV slopes than predicted from disc models even including electron scattering. Instead, what is required to fit this UV downturn is that the emission is much more strongly distorted from a blackbody than predicted in the standard disc. While this could be modeled by a larger colour temperature correction, a shifted blackbody becomes a progressively poorer approximation for the spectrum as $f_{\text{corr}}$ increases. Hence we replace $f_{\text{corr}}$ with a fully Comptonised shape and do not include this factor in our new code as the disc vertical structure is clearly very different to that of Shakura & Sunyaev (1973). Comptonisation also gives the possibility to connect the observed downturn in the UV to an upturn seen in the soft X-ray spectra, forming a single component spanning the unobservable EUV range (D12, Mehdipour et al. 2011, 2015). This warm Comptonising emission could be produced if some fraction of the dissipation takes place higher up in the disc, rather than being concentrated towards the equatorial plane. Residual emission in the denser disc material on the midplane can then act as a source of seed photons, together with the reprocessed emission from illumination from the upper layers of the disc (Petrucci et al. 2017).

Figure 14 in Davis et al. (2005) shows the predicted (colour temperature corrected) blackbody spectrum of a disc annulus where the vertical dissipation goes with density as in standard disc models, compared to one where the dissipation is arbitrarily changed so that 40% of the power is released in the photosphere (Fig. 16 of Davis et al. 2005). The spectrum is strongly Comptonised into a steep tail to higher energies, but clearly contains the imprint of the seed photons as a downturn at low energies. This seed photon temperature is determined both by the intrinsic dissipation in the lower layers of the disc (the remaining 60% of the accretion power in this specific example), and the thermalised flux resulting from irradiation by the Comptonising upper layers. Both these physical processes give seed photons which are close to the surface temperature predicted by the standard disc dissipation, so the seed photon temperature imprinted onto the steep Comptonised emission is itself close to this temperature (Fig. 14 of Davis et al. 2005).

Thus the expectation is that the seed photon energy should change with radius in the same way as the expected standard disc temperature. D12 discuss this in their Appendix, but make the simplifying assumption in OPTXAGNF that this can be approximated as a single Comptonisation spectrum with seed photon temperature set by the maximum temperature of the standard disc emission i.e. $kT_{\text{seed}} = kT_{\text{NT}}(R_{\text{ISCO}})$. This is adequate if the low energy part of this component is mostly unobservable due to interstellar absorption. However, there are now data where this region of the spectrum can be seen, motivating a more
careful approach. Also, the optXAGNF approximation always requires that there is an outer standard disc in order to provide the code with a temperature for the seed photons. This need not be the case in the physical situation envisaged. The warm Comptonisation region could instead cover the entire outer disc as its seed photons are from deeper layers of the underlying disc rather than from an external source.

Petrucci et al. (2017) developed a model where the entire optical/UV/soft X-ray flux is from a warm Comptonisation region. This shows that reprocessing in this geometry hardwires the Compton amplification factor $A$ as

$$A_{\text{seed}} = L_{\text{seed}} + L_{\text{diss,warm}}$$

where $L_{\text{tot}}$, $L_{\text{seed}}$ and $L_{\text{diss,warm}}$ are observed luminosity, seed photon luminosity underneath the coptonising skin and power dissipated in the warm corona, respectively. Their eq. (19) with corona entirely covering the disc and large optical depth with complete thermalisation, gives

$$\frac{L_{\text{diss,warm}}}{L_{\text{seed}}} = A - 1 = 2 \left( 1 - \frac{L_{\text{diss,disc}}}{L_{\text{seed,hot}}} \right) - 1$$

where $L_{\text{diss,disc}}$ is the intrinsic dissipation which thermalises in the disc. If there is no intrinsic dissipation (‘passive disc’ on the midplane: Petrucci et al. 2017) then all these seed photons are set by thermalisation of the warm Compton, and $A = 2$, Thus

$$L_{\text{seed}} = \frac{L_{\text{diss,warm}}}{A - 1} = L_{\text{diss,warm}}$$

so the seed photon temperature should be $T_{\text{NRT}}(R)$. Petrucci et al. (2017) showed that $A = 2$ is equivalent to a photon index of the warm corona component, $\Gamma_{\text{warm}} = 2.5$, which generally gave a good fit to the observed soft X-ray excess component when combined with a Comptonising electron temperature $kT_{e,\text{warm}} \sim 0.2$ keV to give the observed rollover in soft X-rays.

Based on this passive disc picture, our new model, calculates the Compton emission at each annulus of radius $R$ and width $dR$ in the soft corona region, using the nTHCOMP model (Zdziarski, Johnson, & Magdziarz 1996; Życki, Done, & Smith 1999) in XSPEC. We set the seed photon temperature to the local disc temperature $T_{\text{NRT}}(R)$, and set the local luminosity to $\frac{\sigma T_{\text{NRT}}^4(R)}{2\pi RdR} \cdot 2 - 2$, and sum over all annuli which produce the soft Comptonisation.

The green solid line in Fig. 1 shows our new version of the warm Comptonisation, summed over all radii from $r_{\text{warm}} = 40 < R_{\text{ISCO}}$ as in geometry II of Fig.1. We compare this to the AGNSED model for the same parameters (green dashed line), showing the difference in behaviour around the seed photon energy. The blue line in Fig.1 corresponds instead to the geometry of Petrucci et al. (2017) sketched as geometry III in Fig.1, i.e. where there is no outer disc so $r_{\text{warm}} = R_{\text{ISCO}}$. The most noticeable effect is in the normalisation of the disc emission at the lowest energies. This is reduced by a factor $1/(A+1)$. This is important, as it changes the otherwise quite robust relation between the luminosity in some band on the low energy disc tail, and the mass accretion rate. The NT emissivity sets the seed photon temperature and emissivity, but the Comptonisation acts like a colour temperature correction and shifts the entire spectrum to higher energies.

We note here that unlike Petrucci et al. (2017), our new model ties the seed photons for the warm Comptonisation to the parameters of the underlying disc, rather than allowing the seed photon temperature to be a free parameter. Both the warm Comptonisation and standard disc are optically thick, so we assume that the emission is proportional to $\cos i$, where $i$ is the inclination of the disc.

### 2.2 Hot Comptonisation region

There is also an additional X-ray component which dominates over the soft X-ray excess beyond $1 - 2$ keV, extending up to $kT_e \sim 40 - 100$ keV, with $\Gamma \sim 1 - 2$ (Fabian et al. 2015; Lubiński et al. 2016; Petrucci et al. 2017). The low optical depth clearly distinguishes this component from the disc material, and the warm Compton region, so it needs to arise in a different structure. This could either be a corona above a disc, with some fraction of the accretion energy dissipated in this optically thin material, or the optically thick disc could truncate, leaving a true hole inside the inner disc. For $\Gamma \lesssim 0.2$, the hard X-ray photon spectral index is usually $\lesssim 1.9$, i.e. it is flatter than expected even in the limit where all the accretion energy is emitted in the corona. Reprocessing and thermalisation of the (assumed isotropic) illuminating flux even by a completely cold, passive disc, sets a limit on $T_{\text{hot}} \sim 1.9$ (Haardt & Maraschi 1991; Stern et al. 1995; Malzac, Dumont, & Mouchet 2005). Hence we assume that the disc truly truncates at $\theta_{\text{hot}}$, low $\dot{m}$, as is supported by the lack of strong reflection and lack of strong relativistic smearing these AGN (Matt et al. 2014; Yaqoob et al. 2016; Porquet et al. 2018).

In a truncated disc geometry, the seed photons seen by the hot flow are predominantly from the inner edge of the warm Comptonisation region, so these have typical seed photon energy of $T_{\text{NRT}}(R_{\text{hot}}) \cdot \exp(\gamma_{\text{warm}})$, where $\gamma_{\text{warm}} = 4\pi^2 kT_{e,\text{warm}}/m_e c^2$ is the Compton $\gamma$-parameter for the warm comptonising corona. We use the XSPEC model nTHCOMP to describe this, with total power

$$L_{\text{hot}} = L_{\text{diss,hot}} + L_{\text{seed}} \quad (1)$$

Here, the inner flow luminosity, $L_{\text{hot}}$ is the sum of the dissipated energy from the flow, $L_{\text{diss,hot}}$, and the seed photon luminosity which is intercepted by the flow, $L_{\text{seed}}$. This gives $L_{\text{diss,hot}}$ as

$$L_{\text{diss,hot}} = 2 \int_{R_{\text{ISCO}}}^{R_{\text{hot}}} F_{\text{NRT}}(R) \cdot 2\pi R dR$$

$$= 2 \int_{R_{\text{ISCO}}}^{R_{\text{hot}}} \sigma T_{\text{NRT}}(R)^4 \cdot 2\pi RdR \quad (2)$$

with the truncated radius $R_{\text{hot}}$. This is shown geometrically in Fig.2a. Since the X-ray emission is not very optically thick we assume it is isotropic, unlike the disc/warm comptonisation region. $L_{\text{seed}}$ is the intercepted soft luminosity from both the warm Comptonising region and the outer disk. This can be calculated assuming a truncated disc/spherical hot flow geometry (Fig.2a) as

$$L_{\text{seed}} = 2 \int_{R_{\text{ISCO}}}^{R_{\text{hot}}} (F_{\text{NRT}}(R) + F_{\text{rep}}(R)) \frac{\Theta(R)}{\pi} 2\pi R dR \quad (3)$$

$$\Theta(R) = \theta_0 - \frac{1}{2} \sin 2\theta_0 \quad (4)$$

Here, $\Theta(R)/\pi$ is covering fraction of hot flow as seen from the
Figure 2. Geometry geometry of the model. (a) The geometry for hot inner flow (blue), warm Compton emission (green) and outer standard disc (magenta). (b) The lamppost geometry used to simplify the calculation of the reprocessed emission.

2.3 Modeling reprocessing

The assumed geometry shown in Fig. 2a has some fraction of the hot Comptonisation illuminating the warm Comptonisation and cool outer disc regions. We include this self consistently, so that the irradiating flux increases the local flux above that given by the intrinsic $M$. Our geometry assumes that the hot corona is an extended source, with $H \sim R_{\text{hot}}$ (see Fig. 2a). However, Gardner & Done (2017) show that illumination from an extended source can be well approximated by a point source at height $H$ on the spin axis (lamppost: Fig. 2b). We thus utilized the lamppost geometry for the hot inner flow to calculate the reprocessed flux as it is simpler than integrating over an extended source.

The reprocessed flux for a non-spinnning black hole at a radius $R$ is then written as

$$F_{\text{rep}}(R) = \frac{4L_{\text{hot}}}{3\pi(R^2 + H^2)} \frac{H}{\sqrt{R^2 + H^2}} (1 - a)$$

$$= \frac{3GM\dot{M}}{8\pi R^3} \frac{2L_{\text{hot}}}{M c^2} \frac{H}{R} \left(1 - a\right) \left[1 + \left(\frac{H}{R}\right)^2\right]^{-3/2}$$

where $a$ is the reflection albedo. Hence the local flux at radius $R > R_{\text{hot}}$ is $\sigma T_{\text{eff}}(R)^4 = F_{\text{rep}}(R)$. Both $F_{\text{rep}}(R)$ and $F_{\text{rep}}(R)$ depend on radius as $R^{-3}$ for $R \gg R_g$, thus the effect of the reprocessing is basically to increase the flux across both the standard and warm Comptonised disc by the same factor which is of order $H/6R_g$. Hence a larger X-ray source increases the fraction of X-ray power which illuminates the disc, as well as increasing the fraction of bolometric power which is dissipated in the X-ray region via the change in $R_{\text{hot}} = H$.

Figure 3 shows a comparison of example spectra with (solid) and without (dashed) reprocess for a black hole of $10^8 M_\odot$ with $n = 0.05$ (blue) and 0.5 (red). We set $L_{\text{disc,hot}} = 0.02L_{\text{Edd}}$ and $kT_{\text{e,hot}} = 100$ keV for both, which implies $r_{\text{hot}} = 23$ and 9 for $n = 0.05$ and 0.5, respectively. $\Gamma_{\text{hot}}$ is set to be 1.8 and 2.2 for $n = 0.05$ and 0.5, respectively. We also include a warm Comptonisation region with $kT_{\text{e,warm}} = 0.2$ keV and $I_{\text{warm}} = 2.5$. Figure 3a shows models where the warm Comptonisation region extends from $r_{\text{hot}}$ to $r_{\text{warm}} = 2r_{\text{hot}}$, so that there is a standard outer disc region from $r_{\text{warm}}$ to $r_{\text{out}}$ while Fig. 3b shows the alternative geometry where the warm Comptonisation extends over the entire outer disc, i.e. $r_{\text{warm}} = r_{\text{out}}$.

The lower panels of Fig. 3 highlight the effect of reprocessing by showing the ratio of the spectra including reprocessing to the intrinsic emission. Reprocessing makes a larger fraction of the optical emission for the lower $n$, as here the ratio of the X-ray flux to optical disc emission is much larger, and the larger size scale of the X-ray source means that a larger fraction of the X-ray emission is intercepted by the disc. The difference is most marked around the maximum in the SED as the flux increase from reprocessing is enhanced by the associated temperature increase in disc or seed photon energy.

We call this new model AGNSED, and in the appendix define all the parameters. The model is publicly available for use in the XSPEC spectral fitting package.

3 APPLICATION TO OBSERVED SPECTRA

We apply AGNSED to a small sample of AGN, chosen to have very good multi-wavelength data, spanning a wide range of $\dot{m}$, with either very little intrinsic absorption or extremely well determined absorption so that it can be removed without too much uncertainty. We select NGC 5548 (Mehdipour et al. 2015), Mrk 509 (Mehdipour et al. 2011) and PG 1115 + 407 (Jin et al. 2012a,b). We fit the best estimate of the continuum spectra from the AGN, deconvolved from the instrument response, and corrected for reddening and absorption. We read the resulting flux files into XSPEC using the flx2xsp command. These deconvolved data were kindly provided by M. Mehdipour and C. Jin (private communication).

The system parameters for each AGN are given in table 1. We fit all three SED with AGNSED with $i = 45^\circ$ and limit the mass to the uncertainty range given in table 1. The outer disc radius, $r_{\text{out}}$, is initially set to equal to the self-gravity $R_g$.

3.1 NGC 5548: $\dot{m} \sim 0.03$

The Seyfert-1 galaxy NGC 5548 is one of the most widely studied nearby AGN, with well constrained mass (2–6)$\times 10^7 M_\odot$. There was a multi-wavelength campaign on this object in 2012–2014 (e.g., Kaastra et al. 2014), and the broadband spectra were analyzed by Mehdipour et al. (2015). We use the data from summer 2013 shown in Fig. 10 of Mehdipour et al. (2015), with all absorption systems removed. There is strong host galaxy contamination in the optical, so this was also removed (Mehdipour et al. 2015,
There was a large multi-wavelength campaign on this object \citep{Kaastra2011a,Mehdipour2015} fit this by a single, warm Comptonisation region, using blackbody (not disc blackbody) seed photons in order to get such a steeply rising optical/UV continuum. It seems more likely that this is a consequence of a slight oversubtraction of the host galaxy, so we ignore the V and I band continuum points in the fit. The X-ray emission is extremely bright compared to the optical/UV, and very hard (see Fig. 4a).

We then fit the data with AGNSED, including three emission regions. There is a clear iron line in the X-ray data, but no accompanying Compton hump so this line probably originates in optically thin material in the BLR \citep{Yaqoob2001,Brenneman2012,Ursini2015}. We model this simply by including a gaussian in the fit. The model overpredicts the optical data for $R_{\text{out}} = R_g = 880 R_g$ for $n \sim 0.03$. This could again indicate a slight oversubtraction of the host galaxy from our data, but we are able to fit by allowing the outer disc radius to be a free parameter, giving $R_{\text{out}} = 280 R_g$. The overall continuum shape and luminosity is then fairly well reproduced by AGNSED with $n = 0.025$, $R_{\text{warm}} = 160 R_g$, $kT_{\text{warm}} = 2.28$, $kT_{\text{warm}} = 0.17$, and $R_{\text{hot}} = 46 R_g$. $\Gamma_{\text{hot}} = 1.6$, $kT_{\text{hot}} = 39$ keV.

We also try to reproduce the data without any standard outer disc component, as in \cite{Mehdipour2015}. However, in our fit the seed photon energy is not a free parameter, but is set at the underlying disc temperature from reprocessing. The UV data are clearly in tension with this, as they show a stronger downturn than predicted by the warm Comptonisation models with seed photon energy set by the underlying disc area from reprocessing. A warm Comptonisation region covering the outer disc also changes some other aspects of the fit. The lower normalisation in the optical/UV (see Fig. 2, geometry III) means that the same parameters of mass and mass accretion rate cannot match the optical data. The optical flux is $\propto (M M)^{2/3}/A$, where $A$ is the Compton amplification factor (which is unity for the standard disc). Hence including the warm layer across all of the disc means that there should be an increase in $(M M)^{2/3}$ to compensate for the increase in $A$. However, the observed bolometric luminosity $L_{\text{bol}} = \eta M c^2$ is fairly well constrained by the data. Hence the only possibility to increase the optical emission is to increase the mass. This now pegs at the upper limit, giving a slight decrease in $n \sim M/M$.

The outer radius is now not constrained from the data, with little change in goodness of fit from $R_{\text{out}} = 10^3 - 10^5$ so we set this back to the self gravity radius. We show the best fit with these assumptions in Fig. 4b, and tabulate the parameters in Table 2.

3.2 Mrk509: $n \sim 0.1$

Mrk 509 is the nearby Seyfert-1/quasar, and is the first object in which the soft X-ray excess was discovered \citep{Singh1985}. There was a large multi-wavelength campaign on this object \citep{Kaastra2011a,Kaastra2011b}. with simultaneous optical-UV and X-ray monitoring from the XMM-Newton optical monitor (OM) and the European Photon Imaging Camera (EPIC-pn) together with the Cosmic Origins Spectrograph (COS) on the Hubble Space Telescope.
A physical model of AGN SED

3.3 PG 1115+407: $\dot{m} \sim 0.3$

PG 1115+407 is a NLS1 galaxy with mass from single epoch spectra of $4.6 \times 10^7 M_\odot$ using historical data with FWHM Hβ of 1720 km/s (Porquet et al. 2004), or $9.1 \times 10^7 M_\odot$ with the (narrow line subtracted) SDSS FWHM Hβ of 2310 km/s (Jin et al. 2012a). Hence we assumed a black hole mass range of as (0.4-1.4)×10^8 M_\odot, including 0.2 dex uncertainty on the SDSS limit (table 1).

Our SED includes HST, FUSE and the ROentgen SATellite (ROSAT) data (Jin et al. 2012a,b). The steep X-ray continuum means that the signal-to-noise ratio is too limited to constrain any iron line. We fit this SED with AGNSED, and find that the model struggles to fit the observed UV downturn in the FUSE data, even including the outer disc emission. The soft X-ray continuum in ROSAT is also clearly dominated by the warm Comptonisation. Again this is not as good as the best fit model shown in Fig. 4c and detailed in Table 2.

We also try a fit where the entire outer disc is covered by the warm Comptonisation. Again, this is not as good a fit to the UV downturn (Fig. 4d) as the case where the transition radius from the outer disc to warm Comptonisation is around $r_{\text{warm}} \approx 40$, while the observed X-ray emission requires $r_{\text{hot}} \approx 21$. The best fit model is shown in Fig. 4c (and detailed in Table 2).

4 FULL AGN BROADBAND SPECTRAL MODEL

In this section, we evaluate the results of fitting AGNSED to the observed SED of NGC 5548 ($\dot{m} \sim 0.03$), Mrk 509 ($\dot{m} \sim 0.1$), and PG 1115+407 ($\dot{m} \sim 0.3$), and use these, together with other results in the literature, to build a full SED picture where the only free parameters are $M$ and $\dot{m}$.

Table 2. The best estimated parameters. 1 Electron temperature of the hot flow is fixed at 100 keV. † Values in the parenthesis are internally calculated based on the other parameters. ‡ The absolute values of $x$ are not meaningful for deconvolved spectral fit. They are shown only for reference to compare the fit goodness between with and without outer disc. Reflection components are modeled by a single gaussian and gsmooth*Pexmon for NGC 5548 and Mrk 509, respectively. * The values are limited by upper limit of parameters.

| SED Type | $M_\odot$ | $\dot{m}$ | $r_{\text{warm}}$ | $r_{\text{hot}}$ | $L_{\text{hot}}$ | $L_{\text{warm}}$ |
|----------|-----------|-----------|------------------|------------------|----------------|----------------|
| NGC 5548 with outer disc | $5.6 \times 10^7$ | 0.025 | 0.17 | 1.60 | 2.28 | 1.60 |
| Mrk 509 with outer disc | $1.0 \times 10^8$ | 0.10 | 0.20 | 1.96 | 2.36 | 0.49 |
| PG 1115 + 407 with outer disc | $1.1 \times 10^8$ | 0.30 | 0.62 | 2.52 | 2.99 |
| NGC 5548 without outer disc | $6.0 \times 10^7$ | 0.024 | 2.39 | 0.18 | 1.61 | 0.18 |
| Mrk 509 without outer disc | $3.0 \times 10^8$ | 0.441 | 2.59 | 0.28 | 1.87 | 2.27 |
| PG 1115 + 407 without outer disc | $1.4 \times 10^8$ | 0.32 | 3.27 | 1.00 | 2.27 | 2.99 |

$\chi^2$ (dof) | 1.7(1097) | 1.45(370) | 1.037 |

4.1 Existence of an outer standard disc component

All the AGN in section 3 are consistent with AGNSED of three components, where there is an outer disc, together with warm Comptonisation region and hot corona, powered by NT emissivity for a low spin black hole. This is always a better fit than assuming $r_{\text{warm}} = r_{\text{hot}}$, i.e., a model where the warm Comptonisation region extends over the entire outer disc. This is different to the conclusion of Mehdipour et al. (2015) and Petrucci et al. (2017), that the optical/UV data can be fit purely with a warm Comptonisation component. This difference is due to our assumption that the warm Comptonisation is intrinsically linked to a NT disc. The data do fit just as well to an unconstrained warm Comptonisation component as this has the same optical/UV shape as a standard disc (see Fig. 1 geometry III). However, we have
Figure 4. The best estimated models overlayed on the data set of NGC 5548 (Mehdipour et al. 2015, Fig. 10), Mrk 509 (Mehdipour et al. 2011, Fig. 12), and PG 1115+407 (Jin et al. 2012b, Fig. 1). The outer disc emission, the warm compton component, and the hard compton component are shown in magenta, green, and blue, respectively. Panels (a), (b), (c), (d), (e) and (f) correspond to NGC 5548 with and without outer disc, Mrk 509 with and without outer disc and PG 1115 + 407 with and without outer disc, respectively.

additional requirements on the luminosity and seed photon temperature from our assumed NT emissivity. The optically thick, warm Comptonisation suppresses the flux by a factor $A + 1$ below that predicted by the outer disc, so these models require a higher $M$ and/or higher absolute mass accretion rate, $M$, but the latter is fairly well constrained by the observed bolometric luminosity from the broadband spectra. A larger $M$ through the outer disc could be supported if this is counteracted by strong energy losses, e.g., strong wind losses by the UV line driven wind models of Laor & Davis (2014). However, it seems somewhat fine tuned that these wind losses (which vary with mass and $M$) would be almost able to exactly compensate for the extra power predicted by NT emissivity which assumes a constant $M$ with radius. Similarly, high black hole spin would give higher luminosity for a given $M$ through the outer disc, which again would overpredict the total luminosity unless this was entirely dissipated in the unobservable EUV bandpass. Again, this seems fine tuned. The simplest solution is that we are seeing evidence for an outer disc whose properties are like the standard disc, and that the wind losses are small, and spin is low.

4.2 Hot coronal emission

As shown in table 2, the observed power dissipated in the hot inner flow is $L_{\text{diss,hot}} = 0.02 - 0.04 L_{\text{Edd}}$ at all luminosities. This is remarkably consistent with the suggestion of Narayan & Yi (1995) for an advection dominated accretion flow (ADAF) above the critical luminosity, $L_{\text{crit}} = 0.02 L_{\text{Edd}}$. Below this, the ADAF can completely replace the inner accretion disc, but for luminosities above this the flow is dense enough for there to be efficient coupling between the electrons and ions, and the flow collapses back into a standard thin disc. However, they suggested (section 5.3 in Narayan & Yi 1995) that even above this luminosity, the upper layers of the disc are always low enough density to not cool effectively (see e.g., Das & Sharma, 2013), so there is always a hard X-ray corona over the inner disc with luminosity fixed to the maximum ADAF luminosity.

Irrespective of how this is produced, the approximately fixed value for $L_{\text{diss,hot}}$ measured from the data then determines $\Gamma_{\text{hot}}$ from the NT emissivity. For a total $M \sim 0.03$, most of the entire flow energy is needed to power the hard X-ray region, thus $\Gamma_{\text{hot}}$ is large. Conversely, for $M \sim 0.3$, only a very small fraction of the available power is needed to make the hard X-ray flux, so $\Gamma_{\text{hot}}$ is small. Figure 5a shows how the value of $\Gamma_{\text{hot}}$ decreases as a function of increasing $M$ in models where $L_{\text{diss,hot}}$ is fixed at 0.01 (red), 0.02 (green) and 0.05$L_{\text{Edd}}$ (blue). The black stars show the values measured from fitting to the data scatter around the green line, consistent with constant $L_{\text{diss,hot}} = 0.02 L_{\text{Edd}}$, especially considering the uncertainties on mass determination. The predicted decrease in size scale of the X-ray source with increasing $L_{\text{bol}}$, $L_{\text{bol}}$ / $L_{\text{Edd}}$ is compatible with the observations that the X-ray variability timescale decreases with increasing $L_{\text{bol}}$ / $L_{\text{Edd}}$ (McHardy et al. 2006).

In order to examine the validity of the truncated disc / hot flow, we also calculate the self consistent spectral index, $\Gamma_{\text{hot}}$, for the flow. This can be calculated from eq.(14) in Beloborodov (1999) as

$$\Gamma_{\text{hot}} = \frac{7}{3} \left( \frac{L_{\text{diss,hot}}}{L_{\text{seed}}} \right)^{-0.1}$$

With the geometry of truncated inner flow shown in Fig. 2a, $L_{\text{seed}}$ and $L_{\text{diss,hot}}$ are calculated via eq.(2) and (3), respectively. Figure 5b shows the resulting $\Gamma_{\text{hot}}$ assuming $L_{\text{diss,hot}}$ at 0.01$L_{\text{Edd}}$ (red), 0.02$L_{\text{Edd}}$ (green) and 0.05$L_{\text{Edd}}$ (blue). The
data (black stars) are in good agreement with the truncated disc geometry for $L_{\text{disc,hot}} = 0.02L_{\text{Edd}}$.

This truncated disc, hot inner flow geometry results in a spectral index which is not consistent with the observations. However, this geometry is not that suggested by Narayan & Yi (1995) to explain the fixed luminosity, where they rather envisaged a maximal ADAF forming a corona above a thin disc at all luminosities above the ADAF limit. We follow Haardt & Maraschi (1993), (their equation 3a), this slab geometry gives

$$L_{\text{seed}}/L_{\text{Edd}} = (1 - \frac{1}{2}f - \frac{1}{2}f a \alpha)\dot{m}$$

where $f$ is the fraction of power dissipated in the corona. Assuming the constant corona power of $L_{\text{disc,hot}}/L_{\text{Edd}} = \dot{m} = 0.02$, we calculate spectral index expected for a slab geometry and plot it in Fig. 6, where the three lines indicate albedo of $a = 0$ (dotted) 0.3 (solid) and 1 (dashed). The observed data points and prediction for the truncation disc for $L_{\text{disc,hot}} = 0.02L_{\text{Edd}}$ are also included for comparison. The figure clearly shows that the entire slab geometry requires much steeper $\Gamma_{\text{hot}}$ than observed. This problem is discussed in detail also by Pontanen, Vedelina, & Zdziarski (2017) for the case of BHBs in the low/hard state.

Instead, harder spectra can be produced if the corona is localised within $r_{\text{hot}}$, i.e. $f = 1$ above a passive inner disc. However, there is a limit to how hard the spectra can be due to reprocessing in the slab, similar to the discussion for warm Comptonisation in Section 2. The difference here is that the hot Comptonisation spectrum is not very optically thick, so reflection can be important. The lower limit to the seed photon luminosity is $L_{\text{seed}}/L_{\text{Edd}} = 2(1 - a)$. This gives a predicted $\Gamma_{\text{hot}} \leq 1.9$ for an albedo $a > 0.7$ (Fig. 6). Such a high albedo cannot be produced for hard spectra, where the emission peaks above 50 keV as these photons cannot be elastically reflected. Compton downscattering in the disc ensures that a large fraction of the illuminating luminosity is deposited as heat in the disc. This also produces a constant spectral index with increasing $L_{\text{hot}}/L_{\text{Edd}}$, so requires fine tuning of $f$ and $\eta_{\text{hot}}$ in order to produce the observed softening. Hence it seems more likely that the truncated disc / hot inner flow geometry is continued across all $L_{\text{hot}}/L_{\text{Edd}}$.

### 4.3 Warm comptonisation region

The warm Comptonisation region extends from $r_{\text{hot}}$ to an outer radius $r_{\text{warm}} < r_{\text{bg}}$. Ideas which associate this with the changing vertical structure of a disc due to the importance of atomic opacities predict that the warm Comptonisation region should onset at an approximately fixed temperature. One attractive idea is that each annulus of the disc which is at the same temperature as an O star would be modified by a UV line driven wind (Laor & Davis 2014). The maximum disc temperature considering these wind losses is $(2-8) \times 10^4$ K in their models, which is similar to the range seen here for the onset of the warm Comptonisation of $(1-6) \times 10^4$ K. Thus it is possible that the onset of warm Comptonisation does link to the changing disc structure induced by UV opacities, though strong wind losses such as those predicted by Laor & Davis (2014) are ruled out by the observed efficiencies.

This overprediction of wind losses is probably linked...
Table 3. Parameters used in section 5.1 and 5.2. Model (1) and (2) correspond to ‘hot inner flow + warm comptonising skin + outer disc’ and ‘hot inner flow + warm comptonising skin’ (without outer disc), respectively.

| system parameter | $f_{\text{out}}$ | $r_{\text{out}}$ | $r_{\text{in}}$ |
|------------------|------------------|------------------|------------------|
| hot inner flow   | $T_{\text{e,hot}}$ | 100 keV          | calculated via eq. (6) |
| warm compton     | $T_{\text{warm}}$ | 0.2 keV          | 2.5              |
| reprocess        | $r_{\text{warm}}$ | $(1/2)r_{\text{hot},1}$ | $r_{\text{hot}}$ |

5 PREDICTIONS OF THE FULL SED MODEL FOR THE OBSERVATIONAL RESULTS

5.1 UV/X relation

We use the individual AGN fits to define the full SED model in order to compare to a large sample of objects spanning a wide range in $m - M$. Lusso & Risaliti (2017) show that there is a well defined relationship between the UV and X-ray luminosity of AGN, and claim this has low enough scatter to be used as a tracer of the cosmological expansion. Finding the underlying physics is then extremely important, as it can only be used with confidence when it is robustly understood.

Guided by the individual AGN fits above, we fix $L_{\text{disc, hot}} = 0.02 L_{\text{Edd}}$, which defines $r_{\text{hot}}$. We assume that the hot inner flow is quasi-spherical, and that the optically thick flow truncates at $r_{\text{hot}}$, so that the spectral index, $\Gamma_{\text{hot}}$, can be calculated from the ratio of dissipation in the hot region to intercepted seed photons. The best fit models above strongly support a geometry where there are three components (model 1), but again we compare the data to a model where the entire outer disc is covered by the warm Comptonising material (model 2). The inclination angle is expected to be between 0° and 60° for type 1 AGN so we fix this at 45°. Full model parameters are shown in table 3.

We calculate a grid of models spanning $m = 0.03 - 1$ and $M = 10^5 - 10^{10} M_\odot$. Figure 7a shows the resulting relation between the monochromatic luminosity at 2500Å (i.e., 5 eV) and 2 keV, with lines connecting varying $m$ for constant $M$ from our model with an outer standard disc (model 1). Figure 7b shows the slightly different predictions from a model where the warm Comptonisation region covers the entire outer disc (model 2). Both these give a fairly well defined correlation between the UV and X-rays, though with some scatter. We compare these to the best fit UV-X relation derived from 54 SDSS quasars by Lusso & Risaliti (2017) of

$$\log L_{2500\AA} - 25 = 0.633 \cdot (\log L_{2500\AA} - 25) - 1.959$$

(solid black line) on Fig. 7a and b. It is clear that the observed correlation is a slightly different slope than predicted by our models over this entire range. This means that our models models with an outer disc match quite well to the observed relation at high masses, while models with just a warm Comptonisation region are offset by their smaller predicted UV luminosity and match better at low masses.

Our predicted correlation is easy to understand, as it arises due to our assumptions that the X-ray flux is fixed at $L_X = 0.02 L_{\text{Edd}} \propto M$ while the UV is from a disc/comptonised disc so $L_{\text{UV}} \propto (M M_\odot)^{2/3} \propto (M/M_\odot)^{2/3} L_{\text{Edd}}$. Thus this predicts

$$L_X = \frac{1}{2} \log L_{\text{UV}} - \frac{1}{2} \log m + b$$

where $b$ is a constant. There is clearly scatter in the models from $m$, but the requirement to have a BLR selects AGN with $m > 0.02$ (the ADAF limit) in order to have strong UV ionising flux, and we expect superEddington objects to be rare. Thus there is only a limited range of 1.5 dex in $m$, and this reduces to 0.75 dex with the square root factor. However, the data from Lusso & Risaliti (2017) have a scatter of only 0.2 dex.

We study the predicted behaviour in more detail in Fig. 8, using the individual data points from Lusso & Risaliti (2017) (B. Lusso, private communication). These are selected from the SDSS quasar sample, so have absolute i-band magnitude brighter than $-22$. This already

MNDRAS 000, 1–14 (2018)
limits the black hole mass to \( > 10^{7.5} M_\odot \) for objects with a standard disc below Eddington, and the masses reported in (Lusso et al. 2012, Fig.6) are clustered around \( (1 - 10) \times 10^8 M_\odot \). Thus their data only include high black hole masses, so our models with an outer standard disc match well in normalisation and slope to that observed (Fig. 8a), whereas models with complete coverage of the outer disc with a warm Comptonisation underpredict the UV luminosity (Fig. 8b).

Nonetheless, there is still a mismatch between the range predicted by the data and the observed scatter, even for the models with an outer standard disc. The data extend to slightly higher UV luminosity than expected for Eddington limited systems, and do not span across the range expected for the highest mass black holes at the lowest \( \dot{m} \) (Fig. 7a). We suggest that both these mismatches between our model and the data could be due to selection effects. High mass black holes are rarer, so require sampling a larger space volume in order to have a realistic probability of finding some. This means that they are generally seen at larger distances, so are only selected in flux limited samples if they have high luminosity, weighting the selection of high mass black holes towards higher \( \dot{m} \) (including superEddington rates). SuperEddington AGN are seen in the local Universe (Jin, Done, & Ward 2015; Done & Jin 2016; Jin et al. 2017), though they are rare, but their high UV luminosity enhances their probability of selection.

Thus the observed UV-X-ray relation is predicted by our model, where the X-ray luminosity is fixed at the ADAF limit of 0.02L_{Edd} and the UV is from an outer standard disc, with selection effects (mostly the limited range of black hole mass) suppressing some of the predicted scatter. This is a very different explanation to that of Lusso & Risaliti (2017). Their 'toy' model uses the same standard disc equations to estimate the UV flux, but they set the X-ray flux using the gravitational power emitted from the outer disc down to the radius at which the disc becomes radiation pressure dominated. As they note in their paper, producing the X-rays at large radii in the disc rather than close to the black hole is in conflict with microlensing size scales, as well as with the rapid X-ray variability. We suggest that their model works because it effectively hardwires \( L_X \) to a constant value. The radius at which radiation pressure dominates in the disc, \( R_{rad} \), increases as \( \dot{m} \) increases, so leaving a smaller and smaller fraction of power dissipated in the outer disc, and hence reproducing the observed decrease of \( L_X/L_{Bol} \) with \( \dot{m} \) (Vasudevan & Fabian 2007).

Formally, this gives \( R_{rad} \propto (0.002L_{Edd}/\dot{m})^{1/3}(1 - f)^{6/7}R_\odot \), where \( f \) is the fraction of the accretion power which is dissipated in the hard X-ray corona (Svensson & Zdziarski 1994). Then the X-ray luminosity down through the corona from \( R_{out} - R_{rad} \) is

\[
L_X \propto f G M / R_{rad} \propto \alpha^{-2/21} M^{19/21} \dot{m}^{8/21} (1 - f)^{-6/7}
\]

(see their eq.(14) in detail). Hence \( L_X \) is roughly proportional to black hole mass and has only a weak dependence on \( \dot{m} \), so their toy model is almost identical with our assumption of constant \( L_{Bol, hot} \) = 0.02L_{Edd}.

Our model hardwires the same absolute value of \( L_X \), but in a much more plausible geometry where the X-ray source is produced close to the black hole, and with more physical motivation.

### 5.2 Optical variability

The assumption in our SED is that the hard X-rays carry a fixed luminosity. This means that their reprocessed emission, is a similarly fixed luminosity component. However, the X-rays vary rapidly in a stochastic manner about a mean, so their reprocessed emission should also carry the imprint of this rapid variability. This is seen against the remaining, constant component from the disc and/or warm Comptonisation region which increases with \( \dot{m} \). Thus the variable reprocessed emission forms a smaller fraction of the optical/UV emission at higher \( \dot{m} \), which qualitatively matches to what is observed (MacLeod et al. 2010; Ai et al. 2013; Simm et al. 2016; Kozlowski 2016).

Our model explicitly includes the reprocessed emission from X-ray illumination of the outer disc and warm Comptonisation region, so here we calculate the contribution that the varying X-ray emission can make to the optical variability. We illustrate this with our three component SED model (with all parameters as above, tabulated as model (1) in table 3) for AGN of \( 10^8 M_\odot \) with \( \dot{m} = 0.05 \) and 0.5 in Fig. 9a and b, respectively. The black lines show spectra based on the simple NT emissivity including reprocessing, while red lines are the result of stochastic variability (so no impact on \( \dot{m}_{hot} \) etc) increasing \( L_{hot} \) by a factor of 2. The emission from both the outer disc and warm Comptonisation region increases with the increase in \( L_{hot} \), and it is clear that reprocessing makes a much larger fraction of the optical emission at low accretion rates than at high ones.

We quantify the fractional change in optical flux at 4000 Å (3.1 eV), \( \Delta f_{4000}/f_{4000} \), to a factor 2 increase in \( L_{disc,hot} \) across the entire range of AGN masses (\( M = 10^8 \sim 10^{10} M_\odot \)) and mass accretion rates (\( \dot{m} = 0.03 – 1 \)). Figure 10a shows this fractional variability as the colour coding across the grid of log \( M/M_\odot \) and log \( \dot{m} \). It is obvious that lower \( \dot{m} \) gives larger variability, though there is also a much smaller effect where the variability increases with larger mass. This occurs when reprocessing starts to affect the variability at the peak of the warm Comptonisation region, where the temperature shift increases the amplitude of variability (see Fig. 3).

We match this to the observed amplitude of variability seen in a large sample of quasars in SDSS stripe 82. MacLeod et al. (2010) characterised the variability at rest frame 4000 Å with a damped random walk. The mean amplitude of variability in optical magnitudes measured after infinite time is characterised by the structure function extrapolated to infinite time, \( S_F(\infty) \). This is plotted as a function of \( i \)-band magnitude, \( M_i \), and black hole mass in their Fig. 14. In order to compare our models directly to their results, we convert our mass and \( \dot{m} \) to \( M_i \), and convert our fractional variability at 4000Å to a magnitude difference (\( 2.5A \log f_{4000} = \Delta m \)). Figure 10b shows this magnitude difference as a function of black hole mass and \( M_i \) across the whole range of models calculated in Fig. 10a.

Figure 11a shows a zoom of Fig. 10b, limiting it to the same range in mass and \( M_i \) as used by MacLeod et al. (2010). This can then be compared directly against the data in Fig.11b (C. Macleod in private communication). The range in \( M_i \) for each black hole mass spanned by our models at a given \( \dot{m} \) is shown by the cyan lines for \( \dot{m} \) of 0.03, 0.1 and 1. This again stresses the need to use the non-linear
A. Kubota & C. Done.

Figure 7. Monochromatic luminosities $\log L_X$ against $\log L_{\text{UV}}$ for black hole of $M = (0.1 - 1) \times 10^7 M_\odot$ (cyan), $(0.16 - 1) \times 10^8 M_\odot$ (blue), $(0.16 - 1) \times 10^9 M_\odot$ (green), $(0.16 - 1) \times 10^{10} M_\odot$ (red). From left to right $\dot{m}$ changes from 0.03 to 1. The observed UV-X relation in the range of $\log L_{2500} - 25 = 3.8 - 7.4$ (Lusso & Risaliti 2017, Fig. 3) is shown with a solid line. A dashed line is an extrapolation of the solid line. (a) Our three component flow, with an outer disc, warm Comptonisation region and hot inner flow (model 1). (b) A model where there is no standard outer disc (model 2).

Figure 8. Enlargements of Fig. 7 are overlayed on the observed data points in Fig. 3 of Lusso & Risaliti (2017) shown with open grey circles.

conversion between optical flux and bolometric luminosity which is inherent in the standard disc equations. Hence our data with $\dot{m} = 0.03 - 1$ do not span the entire range of $M_i$ which are associated with this range in $\dot{m}$ in Fig. 15 of MacLeod et al. (2010). This makes it plan that the most variable AGN are those with implied $\dot{m} < 0.03$. These plausibly connect to the ‘changing look’ quasars if these are triggered by a state change from an outer disc to an ADAF flow (e.g., Noda & Done in preparation). There are again some AGN with $\dot{m} > 1$. These are rare (Fig. 12 in MacLeod et al. 2010), but they considerably extend the range in $M_i$ for the lowest mass AGN included here.

The colour grid is the same between Fig. 11a and b, and the models with a factor 2 variability in X-rays give the observed amount of optical variability at $\dot{m} = 0.03$. Our models predict a weak trend for higher variability at higher black hole masses, which is opposite to the observed weak trend for higher variability at lower $M$ but this may not be a serious discrepancy as the timescales for the higher mass black holes are longer, so could lead to some variability being missed. A much bigger discrepancy is that the models predict almost no variability at $\dot{m} = 1$, unlike the data which still show variability at the 10% level. This clearly shows that some other component is required to make at least part of the optical variability, though the most rapid variability (e.g. from Kepler light curves: Aranzana et al. 2018) must arise from X-ray reprocessing. An additional source of longer term optical variability also matches with results from more intensive monitoring campaigns which stress the lack of correlation between the X-ray and optical lightcurves (e.g., Arévalo et al. 2009). Gardner & Done (2017) suggest that variability of the soft X-ray excess may play a role, but in our models here this still makes little impact on the optical spectrum at $\dot{m} = 1$. Instead, there should be intrinsic variability in the disc spectrum assuming our disc dominated SED are the correct description of AGN close to the Eddington limit. Standard disc models do indeed predict that AGN discs should be highly unstable due to their dominant radiation pressure, but the non-linear outcome of what should be limit cycle variability is not yet known (Hameury, Viallet, & Lasota 2009 use a heating prescription which goes with only gas pressure to avoid complete disc disruption).

6 SUMMARY AND CONCLUSIONS

We construct a new spectral model $\text{agnsed}$ which includes an outer standard disc, a middle region where the disc is cov-
A physical model of AGN SED

Figure 9. Effects of hard X-ray reprocess for a black hole of $M = 10^8 M_\odot$ with $\dot{m} = 0.05$ (a) and 0.5 (b). SEDs in which the hard X-ray luminosity is increased by a factor of 2.0 (red) are compared with those with Novikov-Thorne emissivity with hard X-ray reprocess (black).

Figure 10. (a) The time variability $\log \Delta f_{4000}/f_{4000}$ are shown as color grid of black hole mass $\log M/M_\odot$ and $\log \dot{m}$. Hot X-ray emission is increased by a factor of 2.0. (b) Same as the top panel but $\log \Delta \text{flux}/\text{flux}$ and $\log \dot{m}$ are converted into $\log \Delta \text{mag}$ at 4000Å and $i$-band absolute magnitude $M_i$. SEDs are based on the parameters of model (1) in table 3.

## Discussion

We fit this model to multiwavelength SEDs of three well observed AGN with very different Eddington ratios, NGC 5548 ($\dot{m} \sim 0.03$), Mrk 509 ($\dot{m} \sim 0.1$), and PG 1115+407 ($\dot{m} \sim 0.3$). The observed spectra are well reproduced with the model, and require an outer standard disc as well as a warm Comptonisation component. This is different to conclusions from previous spectral fits as we constrain our warm Comptonisation component to have seed photons and luminosity from an underlying disc rather than allowing these to be free parameters. The midplane disc is generally passive i.e. the seed photons are produced by reprocessing rather than intrinsic dissipation, which sets the spectral index to $\Gamma_{\text{warm}} = 2.5$ (Petrucci et al. 2017). The transition between the standard disc and warm Comptonisation is always at temperatures consistent with the peak in UV opacity which might point to its origin in the changing disc structure due to failed UV line driven winds (Laor & Davis 2014). The hot plasma has remarkably constant dissipation, consistent with $0.02L_{\text{Edd}}$ for all $\dot{m}$. This implies a smaller size scale with increasing $\dot{m}$, as inferred from X-ray variability (McHardy et al. 2006). The hard X-ray spectral index is consistent with this dissipation always taking place in a region with no underlying disc i.e. a truncated disc/hot inner flow geometry.

Fixing this derived geometry gives a full SED model which depends only on mass and mass accretion rate. This model successfully explains the observed tight UV-X relation shown by Lusso & Risaliti (2017) as a combination of the constant hard X-ray dissipation together with selection effects which mean that the rarer, higher mass quasars are seen preferentially at larger distances so require higher Eddington fractions to be detected. This selection effect introduces scatter and bias but our model gives a physically based understanding these factors, so that the relation can be used to probe cosmology.

The model includes the contribution to the optical/UV flux from X-ray illumination of the outer disc and warm Comptonisation region. We calculate the optical variability resulting from a stochastic change in X-ray flux. This predicts the fast variability in optical should be a strongly decreasing function of Eddington fraction, as the fixed (average) hard X-ray dissipation is a smaller fraction of the bolometric luminosity at higher Eddington ratios. This matches
to some of the trends seen in systematic surveys of AGN variability e.g., SDSS Stripe 82 (MacLeod et al. 2010), but there is more variability seen in high Eddington fraction AGN than predicted. This probably indicate that such highly radiation pressure dominated discs are somewhat unstable. This should motivate theoretical studies to give better understanding of such discs.

ACKNOWLEDGEMENTS

We thank to M. Mehdipour and C. Jin for providing us SEDs in Mehdipour et al. (2011, 2015) and Jin et al. (2012b). We are also grateful to C. Macleod and E. Lusso for providing us the data points in MacLeod et al. (2010) and Lusso & Risaliti (2017), and useful discussions and comments. Special thanks to H. Noda for helpful discussions. AK is supported by research program in foreign country by Shibaura Institute of Technology. CD acknowledges support from STFC (ST/L00075X/1), and useful conversations with O. Blaes and J.M. Hameury.

REFERENCES

Ai Y. L., Yuan W., Zhou H., Wang T. G., Dong X.-B., Wang J. G., Lu H. L., 2013, AJ, 145, 90
Aranzana E., Körding E., Uttley P., Scaringi S., Bloemen S., 2018, MNRAS, 476, 2501
Arévalo P., Uttley P., Lira P., Breedt E., McHardy I. M., Churazov E., 2009, MNRAS, 397, 2004
Beloborodov, A. M. 1999, High Energy Processes in Accreting Black Holes, 161, 295
Boisson B., Ricci C., Faltans S., 2016, A&A, 588, A70
Brenneman L. W., Elvis M., Krongold Y., Liu Y., Mathur S., 2012, ApJ, 744, 13
Crummy J., Fabian A. C., Gallo L., Ross R. R., 2006, MNRAS, 365, 1067
Czerny B., Nikolaou M., Różańska A., Dumont A.-M., Loska Z., Życki P. T., 2003, A&A, 412, 317
Das U., Sharma P., 2013, MNRAS, 435, 2431
Davis S. W., Blaes O. M., Hubeny I., Turner N. J., 2005, ApJ, 621, 372
Davis S. W., Hubeny I., 2006, ApJS, 164, 530
Davis S. W., Woo J.-H., Blaes O. M., 2007, ApJ, 668, 682
Done, C., Davis, S. W., Jin, C., Blaes, O., & Ward, M. 2012, MNRAS, 420, 1848 (D12)
Done C., Gierliński M., Kubota A., 2007, A&ARv, 15, 1
Done C., Jin C., 2016, MNRAS, 460, 1716
Elvis M., et al., 1994, ApJS, 95, 1
Ezhikode S. H., Gandhi P., Done C., Ward M., Dewangan G. C., Misra R., Philip N. S., 2017, MNRAS, 472, 3492
Fabian A. C., et al., 2013, MNRAS, 429, 2917
Fabian A. C., Lohfink A., Kara E., Parker M. L., Vasudevan R., Reynolds C. S., 2015, MNRAS, 451, 4375
Gardner E., Done C., 2017, MNRAS, 470, 3591
Gierliński M., Done C., 2004a, MNRAS, 347, 885
Gierliński M., Done C., 2004b, MNRAS, 349, L7
Haardt F., Maraschi L., 1991, ApJ, 380, L51
Haardt F., Maraschi L., 1993, ApJ, 413, 507
Hameury J.-M., Viallet M., Lasota J.-P., 2009, A&A, 496, 413
Hubeny I., Blaes O., Krolik J. H., Agol E., 2001, ApJ, 559, 680
Jin C., Done C., Middleton M., Ward M., 2013, MNRAS, 436, 3173
Jin C., Done C., Ward M., Gierliński M., Mullaney J., 2009, MNRAS, 398, L16
Jin C., Done C., Ward M., 2015, ebha.conf, 90
Jin C., Done C., Ward M., Gardner E., 2017, MNRAS, 471, 706
Jin C., Ward M., Done C., 2012b, MNRAS, 422, 3268
Jin C., Ward M., Done C., Gelbord J., 2012a, MNRAS, 420, 1825
Kaastra J. S., et al., 2011a, A&A, 534, A36
Kaastra J. S., et al., 2011b, A&A, 534, A37
Kaastra J. S., et al., 2014, Sci, 345, 64
Kozlowski, S., 2016, ApJ, 826, 118
Kubota A., Makishima K., Ebisawa K., 2001, ApJ, 560, L147
Laor A., Davis S. W., 2011, MNRAS, 417, 681
Laor A., Davis S. W., 2014, MNRAS, 436, 3024
Laor A., Fiore F., Elvis M., Wilkes B. J., McDowell J. C., 1997, ApJ, 477, 93
Laor A., Netzer H., 1989, MNRAS, 238, 897
Lawrence A., 2012, MNRAS, 423, 451
Lubiński P., et al., 2016, MNRAS, 458, 2454
Lusso E., et al., 2012, MNRAS, 425, 623
Lusso E., Risaliti G., 2017, A&A, 602, A79
MacLeod C. L., et al., 2010, ApJ, 721, 1014
Maltac J., Dumont A. M., Mouchet M., 2005, A&A, 430, 761
Matt G., et al., 2014, MNRAS, 439, 3016
Matzeu G. A., Reeves J. N., Nardini E., Braito V., Turner T. J., Costa M. T., 2017, MNRAS, 465, 2804
McHardy, I. M., Koerding, E., Knigge, C., Uttley, P., & Fender, R. P. 2006, Nature, 444, 730

Figure 11. (a) Enlargement of Fig. 10b. Black dots represent the places which we calculate. (b) log SF(∞) at 4000Å are plotted in space of $M_i$ and log $M/M_\odot$ (Fig.14 in MacLeod et al. 2010). These data points are given by C.Macleod in private. Colour grid is the same between these two panels. Contours of constant $\Delta$mag in the top panel are overlaid on the bottom panel. Solid cyan lines show constant $\dot{m}$ of 0.03, 0.1 and 1.
APPENDIX A: PARAMETERS OF THE MODEL

We show all the spectral parameters of AGNSED in table A1. The model has some switching parameters. If parameter 4 is negative, the model gives either of the hot inner flow. If parameter 6 is negative, the model gives either of the warm comptonisation component. And if parameter 7 is negative, the model gives either of the outer disc. If parameter 5 is negative then only the warm Compton component is used. If this parameter is negative then only the warm Compton component is used. If this parameter is negative then only the outer disc component is used.

| Table A1. Parameters in AGNSED |
|--------------------------------|
| par1 | mass, black hole mass in solar masses |
| par2 | dist, comoving (proper) distance in Mpc |
| par3 | log \( m = M/M_{\text{Edd}} \) where 0.057\( M_{\text{Edd}}^{-2} = L_{\text{Edd}} \) |
| par4 | \( kT_{e,\text{hot}} \), electron temperature for the hot Comptonisation component in keV. If this parameter is negative then only the hot Compton component is used. |
| par5 | \( \log R_{\text{seed}} \) log of the outer radius of the disc in units of \( R_g \). If this is parameter is negative, the code will use the self gravity radius as calculated from Laor & Netzer (1989). |
| par6 | \( kT_{e,\text{warm}} \), electron temperature for the warm Comptonisation component in keV. If this parameter is negative then only the warm Compton component is used. |
| par7 | \( \Gamma_{\text{warm}} \), spectral index of the warm Comptonisation component. If this parameter is negative then only the warm Compton component is used. |
| par8 | \( \Gamma_{\text{hot}} \), spectral index of the hot Comptonisation component. If this parameter is negative, the code will use the value calculated via eq.(6). |
| par9 | \( L_{\text{disc,hot}}/L_{\text{Edd}} \), the power dissipated in the hot Comptonisation corona in units of \( L_{\text{Edd}} \) |
| par10 | Redshift |
| par11 | \( \Lambda_{\text{hot}}/L_{\text{hot,NT}} \), a factor to increase or decrease luminosity of the hot Comptonisation component from the Novikov-Thorne emissivity; If this is 0, reprocessing is not included. If this is set to be 0 > \( y \) the reprocessing is included and the observed luminosity of the hot inner flow is increased from NT by this factor. If this is 1, reprocessing is included for a simple NT emissivity. |
| par12 | \( a_{\text{hot}} \), albedo of the hot Comptonising corona to the warm Comptonisation component and the outer disc |
| par13 | \( \cos i \), inclination angle \( i \) for the warm Comptonising component and the outer disc. |
| par14 | \( R_{\text{warm}} \), outer radius of the warm Comptonisation component in \( R_g \) |
| par15 | \( H_{\text{max}}/R_g \), the upper limit of the scaleheight for the hot Comptonisation component in units of \( R_g \) |
| par16 | \( kT_{e,\text{cold,hot}} \), seed photon temperature in units of keV for the hot Comptonisation component. If this parameter is negative, the code will use the \( \exp(-y_{\text{warm}}) \cdot kT_{\text{NT,exp}}(R_{\text{hot}}) \) with the y-parameter of the warm Comptonisation, \( y_{\text{warm}} \). |

This paper has been typeset from a \TeX/\LaTeX file prepared by the author.
Figure A1. AGNSED with $M = 1 \times 10^8 \, M_{\odot}$, $D = 100 \, \text{Mpc}$, $\log \dot{m} = -1.3$, $kT_e,_{\text{hot}} = 100 \, \text{keV}$, $\log r_{\text{out}} = -1$ (i.e., $r_{\text{rg}}$), $kT_e,_{\text{warm}} = 0.2 \, \text{keV}$, $\Gamma_{\text{warm}} = 2.5$, $\Gamma_{\text{hot}} = -1$ (i.e., calculated internally), $L_{\text{diss,hot}} = 0.02L_{\text{Edd}}$, $z = 0$, $a = 0.3$, $i = 45^\circ$, $r_{\text{warm}} = 17.8$, $H_{\text{max}} = 150R_g$ and $kT_{\text{compl,hot}} = -1$ (i.e., calculated internally). Black, red and blue lines correspond to without reprocess ($L_{\text{hot}}/L_{\text{hot,NT}} = 0$), with reprocess of $L_{\text{hot}}/L_{\text{hot,NT}} = 1$ and of $L_{\text{hot}}/L_{\text{hot,NT}} = 2$, respectively. The outer disc, the warm Comptonisation component and the hot Comptonisation component are shown with dotted lines from lower to higher energies.