On The Robustness of Cool Disc Components in Bright ULXs

J. M. Miller,[1] A. C. Fabian,[2] and M. C. Miller[3]

[1] *Department of Astronomy, University of Michigan, 500 Church Street, Ann Arbor, MI 48109, USA, jonmm@umich.edu*
[2] *Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA*
[3] *Department of Astronomy, University of Maryland, College Park, MD, 20742, USA*

ABSTRACT
In this letter, we comment on the robustness of putative cool ($kT \simeq 0.2$ keV) accretion disc components in the X-ray spectra of the most luminous ($L_X \simeq 10^{40}$ erg/s) ultra-luminous X-ray sources (ULXs) in nearby normal galaxies. When compared to stellar-mass black holes, the low disc temperatures observed in some ULXs may imply intermediate-mass black hole primaries. Recent work has claimed that such soft excesses are unlikely to be actual disc components, based on the lack of variability in these components, and in the overall source flux. Other work has proposed that alternative phenomenological models, and complex Comptonisation models, rule-out cool disc components in ULX spectra. An inspection of the literature on Galactic stellar-mass black holes and black hole candidates demonstrates that the flux behaviours seen in specific ULXs are consistent with phenomena observed in well-known Galactic X-ray binaries. Applying Comptonisation models to simulated disc blackbody plus power-law spectra shows that at the sensitivity achieved in even the best ULX spectra, Comptonisation fits are highly model-dependent, and do not yield meaningful constraints on the accretion flow. In contrast, the need for a soft, thermal component does not appear to be model-dependent. As we have previously noted, soft thermal components in ULX spectra may not represent accretion discs, but present alternatives to this interpretation are not robust.

Key words: galaxies: normal – X-ray: galaxies

1 INTRODUCTION

The nature of ultra-luminous X-ray sources (ULXs, $L_X \geqslant 2 \times 10^{39}$ erg/s) in nearby normal galaxies has been a topic of great interest in the *Chandra* and *XMM-Newton* era. The apparent luminosity of these sources can exceed the isotropic Eddington limit for a 10 $M_\odot$ black hole, leading to the possibility that some ULXs may harbour intermediate-mass black holes (10^{2-5} $M_\odot$). Initially, this debate was framed in absolute terms, e.g., What is the nature of the ULX phenomenon? Such questions were likely posed in an erroneously simple manner. Every new class of sources is soon divided into subclasses with further study, and is found to be a broad designation covering a heterogeneous group of sources. The fact that Galactic stellar-mass black holes can appear to be mildly super-Eddington (see, e.g., McClintock & Remillard 2005) may argue that many ULXs are stellar-mass black holes. However, a growing subset (fewer than 10 presently) is emerging that may represent a class of intermediate mass black holes.

The lessons learnt from decades of X-ray spectral and timing studies of Galactic stellar-mass black hole binaries and black hole candidates would seem to indicate that a small number of the most luminous ULXs ($L_X \simeq 10^{40}$ erg/s, and above) may harbour black holes of a few hundred or few thousand solar masses (see, e.g., Colbert & Mushotzky 1999; Strohmayer & Mushotzky 2003; Miller

et al. 2003; Cropper et al. 2004; Miller, Fabian, & Miller 2004a; Kaaret, Ward, & Zezas 2004; Miller & Colbert 2004). Intermediate mass black holes are implied in these sources via Eddington luminosity scaling, and/or multi-wavelength properties that argue against beaming, and/or scaling characteristic frequencies found in the X-ray flux, and/or scaling apparent inner disc temperatures in the X-ray spectra.

In the case of inner disc temperatures, intermediate mass black holes may be implied because the temperatures implied ($kT \simeq 0.2$ keV) are well below the temperatures typically measured in stellar-mass black holes accreting near their Eddington limits ($kT \simeq 1 - 2$ keV), and $T \propto M^{-1/4}$ for standard black hole accretion discs (see, e.g., Miller, Fabian, & Miller 2004a). However, the robustness of these soft components has recently been questioned. It has been suggested that the variability properties of ULXs and the soft components in particular, argue against associating them with discs (e.g. Dewangan, Griffiths, & Rao 2005; Goad et al. 2005). Other work has suggested that alternative spectral models may be more appropriate, and may rule-out the possibility of cool discs and intermediate mass black holes in the most luminous ULXs (e.g. Goad et al. 2005, Roberts et al. 2005). In this letter, we examine these arguments in detail, in the context of better-understood Galactic stellar-mass black hole binaries and AGN.

2 ON DISC TEMPERATURE AND FLUX VARIATIONS

While some broad expectations can be derived from robust theoretical considerations, the detailed phenomenology of accretion discs and their inner workings are poorly understood at present. One such simple expectation is that disc temperature should directly correlate with disc flux, assuming apparent disc flux is a good proxy of the mass accretion rate through the disc. Dewangan, Griffiths, & Rao (2005) have recently claimed that the cool, soft component in the X-ray spectrum of NGC 1313 X-1 may not actually be an accretion disc because "its blackbody temperature is similar in three XMM-Newton observations, despite a change in the observed flux by a factor of about two." In the absence of a detailed theoretical understanding of accretion discs, insight may be gained by examining the observed behaviour of stellar-mass black holes and black hole candidates. In these systems, both the presence of accretion discs and their manifestation in X-ray spectra are beyond doubt at high mass accretion rates.

The temperatures measured in NGC 1313 X-1 by Dewangan, Griffiths, & Rao (2005) range between kT= $0.14 - 0.21$ keV, depending on the model and spectrum. In fits which apply the same soft component model to different source flux levels, the measured temperature variations range between 5–20%. The rich literature on the behavior of Galactic black holes clearly shows that disc components in these better-understood systems can manifest exactly such behaviour. In the Galactic black hole 4U 1543$-$47, Park et al. (2004) report temperature variations as small as 6% over a factor of 2.1 in disc flux (obs. 18 versus obs. 24). In XTE J1550$-$564, Sobczak et al. (2000) report disc temperature variations as small as 4% over a factor of 2.8 in disc flux (obs. 152 versus obs. 156). In GRO J1655$-$40, Sobczak et al. (1999) show that the disc temperature can differ by as little as 5% over a factor of more than 4.0 in disc flux (1996 Oct. 27 versus Nov. 02). In 4U 1630$-$472, Trudolyubov, Borozdin, & Priedhorsky (2001) show that the disc temperature can vary by as little as 1% across a factor of 2.9 in disc flux (obs. 3 versus obs. 31). Finally, in XTE J1748$-$288, Miller et al. (2001) report a temperature variation of only 2% across a factor of 5.3 in disc flux (obs. 8 versus obs. 9).

Clearly, based on a comparison with Galactic black holes, the fact that a temperature–flux relation does not hold at all times does not preclude associating a soft thermal component with an accretion disc.

3 ON FAST X-RAY VARIABILITY

Goad et al. (2005) claim that the absence of fast variability in the broad-band X-ray flux of Ho II X-1 argues against the presence of an intermediate mass black hole, and against the possibility that the soft excess in this ULX arises from a cool accretion disc. This argument is based on the premise that low fractional variability is not observed at low fractional Eddington accretion rates in stellar-mass black holes and black hole candidates. However, existing literature shows that this is incorrect. Smith et al. (2001) report that the fractional variability in GRS 1758$-$258 dropped to values consistent with zero, in a low-flux state (approximately 0.04 $L_{Edd.}$ for a 10 $M_\odot$ black hole at $d = 8.5$ kpc) dominated by cool disc emission. In an observation of 4U 1957+11 at 0.05 $L_{Edd.}$ (for a 10 $M_\odot$ black hole at $d = 7$ kpc), Wijnands, Miller, & van der Klis (2002) report a total fractional variability of only 1.4% where the hard component is still 88% of the total flux (see obs. 9).

Clearly, low fractional variability is possible at low flux levels in stellar-mass black holes and black hole candidates. We note that episodes of low fractional variability are not frequent in stellar-mass black holes and black hole candidates, but they are observed, and less extreme examples are more common. Thus, low fractional variability cannot be used to argue against applying the same spectral interpretations to ULX spectra that are used in stellar-mass black holes and black hole candidates.

4 ON PHENOMENOLOGICAL SPECTRAL MODELS

It is common to model the spectra of accretion-powered sources with simple, phenomenological models, usually consisting of a thermal disc component at low energy and a hard (sometimes non-thermal) power-law-like component at high energy. Models of this sort reflect the basic expectation that a thermal accretion disc, and hard emission from the inverse Compton scattering of disc photons, should be the dominant sources of emission in accreting black holes. It has been claimed that the roles of these components can be flipped in the spectra of some ULXs; that is, the low energy emission might be dominated by a steep power-law component, and the hard emission might be dominated by a very hot blackbody component (e.g. Roberts et al. 2005). While such fits may be statistically permissible in spectra of poor sensitivity, and/or in dipping phases, it is worth examining whether or not there is any physical justification or any precedent for such a model in ordinary phases.

A component arising from the inverse-Compton scattering of disc photons cannot dominate the disc flux below the peak of the blackbody distribution, so an alternative explanation for the hard component is required. It is possible that the hard component is partly or even mostly due to synchrotron emission from a jet (e.g. Markoff, Fender, & Falcke 2001). In this case, (depending partially on whether or not the jet power-law has a break) the power-law distribution might extend to low energy and dominate both below and above the disc blackbody distribution. This scenario might broadly correspond to one in which cool thermal and hard non-thermal components could be flipped. However, jets are only predicted to contribute significantly to the X-ray flux in the "low/hard" state; if ULXs with implied luminosities near 10^{40} erg/s are in a low/hard state, then they are accreting at a small fraction of their Eddington limits, and intermediate-mass black holes would still be implied by their luminosity. Moreover, in such states, hard power-law components are typically observed; $\Gamma = 1.5 - 1.7$ is common. The power-laws required in flipped spectral models of ULXs are extremely soft, with $\Gamma = 3 - 4$. There is no evidence for steady jet production in stellar-mass black holes and black hole candidates, in states with such steep power-law indices. Given that such models are not dramatically better fits than standard models and that better-understood black holes do not manifest the behaviour implied, it seems likely these models only reflect statistical (not physical) possibilities.

5 COMPLEX COMPTONISATION MODELS: THE ECHOES OF INTENTION

The power of simple phenomenological spectral models is that they can be tightly constrained, even when fitting spectra of limited sensitivity. Compared to the best AGN and stellar-mass black hole spectra, present ULX spectra are certainly of that type. More physically-motivated models, many of which attempt to e.g. properly calculate the up-scattering of disc X-rays in a corona, predict subtle curvature which is difficult to detect in low signal-to-noise

spectra. Moreover, such models come with a price: additional parameters. A model consisting of disc blackbody and power-law components, modified by line of sight absorption, has 5 parameters. Replacing the power-law component with a simple Comptonisation model – "compTT" – drives the number of model parameters up to 9. A model which employs a full code such as "eqpair" (Coppi 2002), which includes a disc distribution, has 21 model parameters after adding one parameter to account for line-of-sight absorption. At the signal-to-noise typical of present ULX spectra, the parameters of complex models cannot be regarded as reliable. The resultant fits will (by force) reflect the assumptions of the model and biases of the modeler in such circumstances. Moreover, resultant fits are likely to be statistically degenerate with fits obtained using the same model with different bounds or choices for given parameters.

In order to illustrate that even simple Comptonisation models can not only yield degenerate results based only on assumptions, but can actually yield incorrect "constraints" on the accretion flow, we have simulated a disc blackbody plus power-law spectrum and fit it with a basic Comptonisation model. The power of this approach is that the nature of the spectrum is known a priori, and the ability of complex models to distort an intrinsically simple spectrum or provide false information is effectively tested.

The simulated spectral parameters were taken from disc blackbody plus power-law fits made to NGC 1313 X-1 and reported in Miller, Fabian, & Miller (2004b). The parameters for the simulated spectrum are as follows: $N_H = 3.1 \times 10^{21}$ cm^{-2}, $kT_{dbb} = 0.23$ keV, $N_{dbb} = 28$, $\Gamma = 1.76$, $N_{pl} = 4.9 \times 10^{-4}$ ph cm^{-2} s^{-1}. The same *XMM-Newton*/EPIC-pn "primefullwindow" mode (plus medium optical blocking filter) response files were used to generate a simulated 100 ksec EPIC-pn spectrum, using the XSPEC task "fakeit". Note that this simulated observation is as long as the longest single observation of any ULX obtained with *XMM-Newton*. Only Poisson noise is included in simulating a spectrum in this way; in generating and fitting the simulated spectrum, we considered no additional noise or background. In effect, then, the simulated spectrum is of a higher sensitivity than any ULX spectrum yet obtained.

Prior to fitting, the simulated spectrum was grouped to require 10 counts/bin using the FTOOL "grppha" to ensure the accuracy of χ^2 fitting results. Spectral fits were made in the 0.3–10.0 keV band using XSPEC 11.3.2. Reported errors on fit parameters are 90% confidence errors for one parameter of interest. The simple Comptonisation model used consisted of a disc blackbody component, and the "compTT" thermal Comptonisation model, modified by line-of-sight absorption.

A statistically acceptable fit to the simulated spectrum can be obtained with a low-temperature, optically-thick corona similar to the fits spectra of Ho II X-1 reported by Goad et al. (2005). Of course, in the simulated spectrum, there is no component which directly corresponds to such a low-temperature, optically-thick corona. With this model, we obtain the following parameter values: $N_H = 2.8(3) \times 10^{21}$ cm^{-2}, $kT_{dbb} = 0.23(3)$ keV, $N_{dbb} = 20(4)$, $T_{seed} = 0.41(3)$ keV, $kT_e = 6.8(3)$ keV, $\tau = 4.1(2)$, and $N_{compTT} = 9.3(2) \times 10^{-5}$, and a formally acceptable fit statistic of $\chi^2/dof = 1226/1245$. Let us refer to this model as "CM1". In this fit, we fixed the redshift parameter in "compTT" to be equal to zero, and the approximation flag equal to unity (corresponding to a disc plus corona geometry).

It is also possible to obtain a statistically acceptable fit to the simulated spectrum, with a hot, optically-thin corona. Comptonisation in a hot corona should produce less spectral curvature, and should better correspond to a simple power-law, though we again note that there is of course no Comptonisation component in the simulated spectrum. With this model, we obtain the following parameter values: $N_H = 2.7(3) \times 10^{21}$ cm^{-2}, $kT_{dbb} = 0.22(2)$ keV, $N_{dbb} = 33(4)$, $T_{seed} = 0.22(3)$ keV, $kT_e = 49(3)$ keV, $\tau = 0.83(3)$, and $N_{compTT} = 2.1(1) \times 10^{-5}$, and a formally acceptable fit statistic of $\chi^2/dof = 1228/1245$. Let us refer to this model as "CM2". The incredible similarity of this spectral model to that detailed above, despite very different model parameters and a very different physical picture, is depicted in Figure 1.

Statistically acceptable fits can also be achieved using broken power-law or exponentially cut-off power-law models, though the simulated power-law contains neither a break nor a cut-off. Using a broken power-law, the following parameters were obtained: $N_H = 2.7(2) \times 10^{21}$ cm^{-2}, $kT_{dbb} = 0.29(2)$, $N_{dbb} = 7.3(9)$, $\Gamma_1 = 1.71(2)$, $E_{br} = 5^{+2}_{-1}$ keV, $\Gamma_2 = 1.82(7)$, $N_{pl} = 4.3(1) \times 10^{-4}$ ph cm^{-2} s^{-1}, and $\chi^2/\nu = 1220/1258$. We note that a break with $\delta(\Gamma) = 0.3$ can also be accommodated, statistically. Using an exponentially cut-off power-law, the following parameters are obtained: $N_H = 2.3(2) \times 10^{21}$ cm^{-2}, $kT_{dbb} = 0.34(3)$, $N_{dbb} = 4.3(8)$, $\Gamma_1 = 1.1(1)$, $E_{cut} = 7.7(3)$ keV, $N_{pl} = 3.1(1) \times 10^{-4}$ ph cm^{-2} s^{-1}, and $\chi^2/\nu = 1228/1259$. Breaks and cut-offs are merely possible, not required, in present ULX spectra.

We also simulated 100 ksec spectra, based on the parameters obtained in CM1 and CM2. The simulated spectrum based on CM1 can be fitted with a model that has the following parameters: $N_H = 2.6(2) \times 10^{21}$ cm^{-2}, $kT_{dbb} = 0.12(2)$ keV, $N_{dbb} = 110(60)$, $T_{seed} = 0.14(2)$ keV, $kT_e = 53(3)$ keV, $\tau = 0.89(4)$, and $N_{compTT} = 2.3(2) \times 10^{-5}$, yielding an acceptable fit statistic of $\chi^2/dof = 1307/1245$. The simulated spectrum based on CM2 can be fitted with the following model parameters: $N_H = 2.2(2) \times 10^{21}$ cm^{-2}, $kT_{dbb} = 0.28(3)$ keV, $N_{dbb} = 5.2(9)$, $T_{seed} = 0.17(2)$ keV, $kT_e = 6.0(2)$ keV, $\tau = 4.2(2)$, and $N_{compTT} = 1.8(2) \times 10^{-4}$, yielding an acceptable fit statistic of $\chi^2/dof = 1094/1245$. That is, at the sensitivity of the best present ULX spectra, a cool optically-thick coronal spectrum can be fitted with a hot, optically-thin model, and vice versa.

Clearly, even simple Comptonisation models cannot be used to infer the nature of the corona in present ULX spectra. Although the nature of the corona cannot be inferred reliably, the results detailed above show that the assumed nature of a hard spectral component does not strongly affect the need for a soft component, or the temperatures derived when this component is fit with a disc model. This is true when working with real data as well: Goad et al. (2005) require a cool disc to obtain a good fit to the spectrum of Ho II X-1, though its significance is dismissed based on the Comptonisation component fit to that spectrum.

Whereas one might expect that the parameters of Comptonizaton models merely cannot be constrained reliably at the signal-to-noise achieved in ULX spectra, the true situation is in fact much worse: even simple Comptonisation models can easily be manipulated to give the answer the observer wants, and that answer can in fact be entirely incorrect though statistically acceptable. This finding calls into question the validity of the models considered and the utility of these and yet more sophisticated models (e.g. eqpair, see Roberts et al. 2005) in the ULX regime.

Phenomenological spectral models, while perhaps physically naive, are robust and useful in that their parameters can be constrained reliably. Fits with such models are reproducible, falsifiable, and therefore meaningful. They provide a common currency through which different sources can be compared consistently. Complex models which are not statistically required, and which

are highly malleable, cannot be falsified, and therefore necessarily fail to provide scientific insights.

6   SUMMARY AND CONCLUSIONS

We have shown that a variety of arguments against interpreting apparent cool thermal components in the spectra of very luminous ULXs are contradicted by published results from stellar mass black holes and black hole candidates, by simple physical considerations, and by critically examining the ability of complex models to yield meaningful results in low signal-to-noise regimes. The absence of direct correlations between apparent disc temperatures and fluxes observed in some ULXs is a phenomenon commonly observed in stellar-mass black holes and black hole candidates. Moreover, limited fast X-ray variability has been observed in stellar-mass black holes and black hole candidates, even in hard phases at low fractional Eddington luminosities. Spectroscopy of stellar-mass black holes and physical considerations strongly argue for associating thermal distributions with the low energy portion of a spectrum, and scattered or non-thermal distributions with the high energy portion. Finally, we have shown that even at the sensitivity achieved in the best present ULX spectra, complex Comptonisation models can yield false inferences and give an incorrect picture of the accretion flow geometry.

In the case of NGC 1313 X-1 and M81 X-9, present spectra have been sufficient to show that cool disc plus power-law models are at least 5σ better than single-component models, broken power-law models, and models with significantly sub-solar abundances in gas along the line of sight (Miller et al. 2003; Miller, Fabian, & Miller 2004b). The same work has shown that cool discs are robust against specific choices of disc models and specific choices of hard component models. Even in cases where Comptonisation models are invoked to argue against interpreting soft excesses as discs, cool disc components are required to achieve acceptable fits (e.g. Goad et al. 2005). This further highlights the robustness of cool thermal components, and the perils of Comptonisation models in low signal-to-noise spectra.

The cool disc interpretation is merely the most plausible one, based on a comparison to other black holes, and principally stellar-mass black holes. As we have previously noted, however, cool thermal components in the spectra of very luminous ULXs are not necessarily disc components, and not all soft components in the spectra of accreting black holes are well-understood. The soft excess observed in some Seyfert-1 galaxies is too hot to easily be attributed to a disc, and its nature is uncertain. Miller, Fabian, & Miller (2004a) noted this aspect of Seyfert-1 spectra, in anticipation of the possibility that some of the ULXs which have cool thermal components may actually be background AGN. Indeed, this proved to be the case for the ULX Antennae X-37 (Clark et al. 2005). It is possible that the soft excess in genuine ULXs is similar to that in some Seyfert-1 spectra. However, if both phenomena are due to relativistically-blurred disc emission lines (Crummy et al. 2005), then the soft component in ULXs indicates that the emission is isotropic and intermediate-mass black holes may still be required via simple Eddington scaling arguments. We note that a preliminary investigation we have undertaken reveals that *XMM-Newton* spectra of ULXs with apparent cool thermal components can also be fit acceptably with blurred disc reflection models.

While this letter demonstrates that cool thermal components are likely more robust than than inferences derived from models for the hard component in ULX spectra, it also serves to demon-

strate that present ULX spectra are intrinsically a low signal-to-noise regime. All spectral fits, whether simple or complex, must be regarded cautiously in such circumstances, but the most robust conclusions probably derive from simple models that can be constrained by the data. Very deep observations of ULXs with *XMM-Newton* (350 ksec or longer) may be the only means of parsing the nature of soft and hard components in very luminous ULXs in more detail.

REFERENCES

Dewangan, G., C., Griffiths, R. E., & Rao, A. R., 2005, ApJ, subm., astro-ph/0511112
Clark, D. M., et al., 2005, ApJ, 631, L109
Colbert, E. J. M., & Mushotzky, R. F., 1999, ApJ, 519, 89
Cropper, M., et al., 2004, MNRAS, 349, 39
Crummy, J., Fabian, A. C., Gallo, L., & Ross, R., 2005, MNRAS, in press, astro-ph/0511457
Goad, M. R., Roberts, T. P., Reeves, J. N., & Uttley, P., 2005, MNRAS, in press, astro-ph/0510185
Kaaret, P., Ward, M., & Zezas, A., 2004, MNRAS, 351, L83
Markoff, S., Falcke, H., & Fender, R., 2001, A&A, 372, L25
McClintock, J., & Remillard, R., 2005, in "Compact Stellar X-ray Sources", eds. M. van der Klis and W. H. G. Lewin, Cambridge (CUP)
Miller, J. M., Fabbiano, G., Miller, M. C., & Fabian, A. C., 2003, ApJ, 585, L37
Miller, J. M., Fabian, A. C., & Miller, M. C., 2004a, ApJ, 614, L117
Miller, J. M., Fabian, A. C., & Miller, M. C., 2004b, ApJ, 607, 931
Miller, M. C., & Colbert, E. J. M., 2004, International Journal of Modern Physics D., 13, 1
Park, S. Q., et al., 2004, ApJ, 610, 378
Roberts, T. P., et al., 2005, in the proceedings of "The X-ray Universe 2005", San Lorenzo de El Escorial, 26-30 Sept. 2005, astro-ph/051107
Smith, D. M., Heindl, W. A., Markwardt, C. B., & Swank, J. H., 2001, ApJ, 554, L41
Sobczak, G. J., et al., 1999, ApJ, 520, 776
Sobczak, G. J., et al., 2000, ApJ, 544, 993
Strohmayer, T., & Mushotzky, R., 2003, ApJ, 586, L61
Trudolyubov, S. P., Borozdin, K. N., & Priedhorsky, W. C., 2001, MNRAS, 322, 309
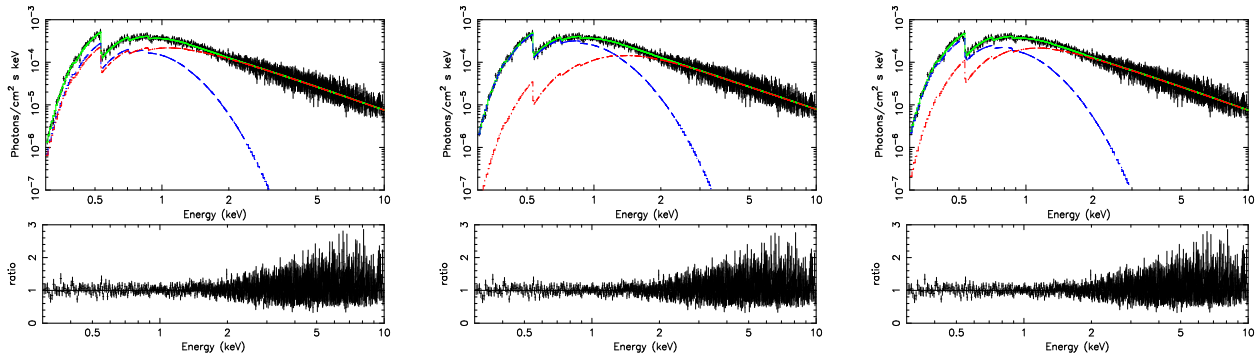Wijnands, R., Miller, J. M., & van der Klis, M., 2002, MNRAS, 331, 60

Figure 1. The figure above shows the results of model fits to a simulated spectrum consisting of disc blackbody and power-law components. The fit shown in the left panel was obtained using disc blackbody and power-law components. The fit shown in the middle panel was obtained using a model consisting of a disc blackbody and a cool ($kT = 6.8$ keV), optically-thick ($\tau = 4.1$) Comptonising coronal component. The fit shown in the right panel was obtained using a model consisting of a disc blackbody and a hot ($kT = 48$ keV), optically-thin ($\tau = 0.8$) Comptonising coronal component. Although the fits are statistically equivalent, it is clear that very different Comptonisation models produce only minor changes in the 0.5–10.0 keV band, and both Comptonisation models yield false implications about the simulated spectrum.