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PATCHY ACCRETION DISKS IN ULTRALUMINOUS X-RAY SOURCES

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ABSTRACT

The X-ray spectra of the most extreme ultra-luminous X-ray sources – those with $L \geq 10^{40}$ erg s^{-1} – remain something of a mystery. Spectral roll-over in the 5–10 keV band was originally detected in in the deepest *XMM-Newton* observations of the brightest sources; this is confirmed in subsequent *NuSTAR* spectra. This emission can be modeled via Comptonization, but with low electron temperatures ($kT_e \simeq$2 keV) and high optical depths ($\tau \simeq 10$) that pose numerous difficulties. Moreover, evidence of cooler thermal emission that can be fit with thin disk models persists, even in fits to joint *XMM-Newton* and *NuSTAR* observations. Using NGC 1313 X-1 as a test case, we show that a patchy disk with a multiple temperature profile may provide an excellent description of such spectra. In principle, a number of patches within a cool disk might emit over a range of temperatures, but the data only require a two-temperature profile plus standard Comptonization, or three distinct blackbody components. A mechanism such as the photon bubble instability may naturally give rise to a patchy disk profile, and could give rise to super-Eddington luminosities. It is possible, then, that a patchy disk (rather than a disk with a standard single-temperature profile) might be a hallmark of accretion disks close to or above the Eddington limit. We discuss further tests of this picture, and potential implications for sources such as narrow-line Seyfert-1 galaxies (NLSy1s) and other low-mass active galactic nuclei (AGN).

Subject headings: accretion disks – black hole physics – X-rays: binaries

1. INTRODUCTION

Ultra-luminous X-ray (ULXs) are accretion-powered sources that appear to violate the isotropic Eddington limit for a fiducial $M = 10\ M_{\odot}$ black hole. In practice, a better lower limit is $L_X \geq 2 \times 10^{39}$ erg s^{-1} (Irwin, Athey, & Bregman 2003). Most or all of the sources that barely qualify as ULXs are likely to be stellar-mass black holes similar to those known in the Milky Way. The set of ULXs with $L_x \geq 10^{40}$ erg s^{-1} is far more interesting, as these sources more strongly indicate super-Eddington accretion or elevated black hole masses.

Only a small number of these extreme ULXs are found at distances that permit sensitive spectra in reasonable observation times (note that Sutton et al. 2012 and Gladstone 2013 define "extreme" differently). Yet, detailed studies have revealed multiple components in the spectra of these ULXs, including soft disk–like components. The low temperature values typical of these components ($kT \simeq 0.2$ keV) may indicate accretion onto more massive black holes (e.g. $10^{2-3}\ M_{\odot}$; Miller et al. 2003, 2004, 2013). Mass estimates depend strongly on numerous assumptions (e.g. Soria 2011, Miller et al. 2013), not least the idea that black holes in ULXs accrete in a mode that is observed in sub-Eddington stellar-mass black holes and in AGN.

However, ULXs may show spectral phenomena that stellar-mass black holes and AGN may not. In particular, deep *XMM-Newton* spectra show evidence of a roll-over in the 5–10 keV band. This peculiar hard component can also be modeled as Comptonization of low temperature photons (e.g. Stobbart et al. 2006, Gladstone et al. 2009). In constrast to the hot, optically–thin Comptonization regions inferred in other black holes, the roll-over in ULXs requires a cool, optically–thick region ($kT_e \simeq 2$ keV; $\tau \simeq 10$). Unless the corona is heated locally and/or powered magnetically – in some manner that would prevent substantial heating – it is easy to show that such a cool corona must be huge in order to generate the bulk of the observed $L_X \geq 10^{40}$ erg s^{-1} that is observed (see, e.g., Merloni & Fabian 2001 concerning thermal and magnetic coronae). Not only is it difficult to envisage a very large region that can be characterized by a single temperature, but the outer part of the putative corona may only be marginally bound to the black hole.

Some extreme ULXs have been detected up to 40 keV in recent *NuSTAR* (Harrison et al. 2013) observations, and the roll–over found in prior 0.3–10.0 keV spectra is strongly confirmed (e.g Walton et al. 2013a, 2014; Bachetti et al. 2013; Rana et al. 2014). Low–temperature Comptonization again provides acceptable fits, but again is not a unique description, and the problems of such coronae remain.

Putative Comptonization components with such low electron temperatures and high optical depths, are fairly similar to a blackbody (e.g. Stobbart et al. 2006; Kajava et al. 2012; Middleton et al. 2011). Miller et al. (2013) recently reported positive correlations between the temperature and luminosity of the cool ($kT \simeq 0.2$ keV) disk–like components in ULXs, suggesting that a disk interpretation may be also be correct or that component (less stringent data selection and modeling previously led to different conclusions; see Kajava & Poutanen 2009; Pintore & Zampieri 2012). In view of that result – and the blackbody–like nature of the harder component that rolls-over at high energy – Miller et al. (2013) suggested that both components may originate in the disk, and that ULX spectra may be consistent with "patchy" or inhomogeneous disks (see Dexter & Quataert 2012; also see Begelman 2002, Dotan & Shaviv 2011). This Letter explicitly examines the possibility of inhomogeneous disks in extreme ULXs.

2. DATA REDUCTION

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NGC 1313 X-1 was selected as our test case because it has been observed on numerous occasions with *XMM-Newton*, and on two occasions with both *XMM-Newton* and *NuSTAR*. The data considered in this work are exactly the data from two epochs of observations treated in Bachetti et al. (2013), and the reader is referred to that paper for details of the observations and data reduction.

Again following Bachetti et al. (2013), we fit the *XMM-Newton*/EPIC-pn and EPIC-MOS2 spectra in the canonical 0.3–10.0 keV band, and the *NuSTAR*/FPMA and FPMB spectra in the 3–30 keV band. However, whereas Bachetti et al. (2013) adopted different grouping schemes for the *NuSTAR* data depending on the behaviors of specific models, we binned every spectrum to require at least 20 counts per bin for every model (in order to ensure the validity of χ^2 statistics; Cash 1979). Grouping was accomplished using the FTOOLs suite (specifically "grppha") and all spectral fits were made using XSPEC version 12.8.0 (Arnaud 1996).

The spectral fits were made allowing an overall multiplicative constant to float between them. All other parameters were linked across different spectra and jointly determined by the fit. Last, in all fits, the absorption along the line of sight was characterized using a single *tbabs* model with the proper abundances and cross sections (Wilms, Allen, & McCray 2000). All uncertainties in this work are 1σ confidence errors.

3. ANALYSIS AND RESULTS

As an initial test of the viability of a patchy disk explanation for ULX spectra and accretion flows, we fit a model consisting of two "diskbb" components (Mitsuda et al. 1984) to the spectra from both epochs. The hotter component may be a simple blackbody, but if the various patches are distributed over even a small range in disk radius, they may also have a small run in temperature, and a disk blackbody profile is not unreasonable.

As can be seen in Figure 1, most of the observed spectra can be accounted for with such a model, including the putative thermal, disk–like component at low energy, and the harder component peaking around $\simeq$5 keV and rolling-over to 10 keV. This simple model is even a relatively good fit, yielding χ^2/ν = 1.07 (see Table 1). It is clear, however, that the two disk components fail to fit all of the high energy flux captured with *NuSTAR*. Moreover, these fitting results are not as good as those achieved in fits to similar data in Miller et al. (2013), nor as good as fits to the exact same spectra in Bachetti et al. (2013).

In order to capture the additional high energy flux, we next considered models that added different Comptonization prescriptions. The "compTT" component is a physical model that allows the electron temperature of the corona (kT_e) and its optical depth (τ) to be measured directly (Titarchuk 1994). As noted above, it is often fit in combination with "diskbb" components, even when modeling ULX spectra. A model consisting of two independent "diskbb" components, each with a corresponding "compTT" component ($diskbb+compTT+diskbb+compTT$), was therefore explored. The seed photon temperature in each "compTT" component was linked to the temperature of its corresponding disk component, but the "compTT" electron temperatures, optical depths, and flux normalizations were allowed to float independently.

Excellent fits were obtained with this model ($\chi^2/\nu \simeq$ 1.00), but the Comptonization parameters were largely unconstrained. As just one example of the kind of Comptonization that might account for the hard flux, the electron temperature and optical depth were fixed at kT_e = 100 keV and τ = 0.1, respectively. Such values are representative of the coronae inferred in better–understood black holes. Indeed, in the "very high" or "steep power-law state" – to which ULXs may bear some resemblance – the electron temperature may be even higher (Tomsick et al. 1999). With this simplification, excellent fits were again achieved (see Figures 2 and 3, and Table 1). Importantly, the overall fit to each epoch was improved by $\Delta\chi^2 > 100$ relative to fits without Comptonization (see Table 1). This model merely represents one simplistic description of Comptonization, that makes contact with the coronae and Comptonizing regions implied in more familiar Galactic black holes. Future explorations of ULX spectra in terms of patchy disks may need to examine different, less idealized possibilities.

Next, we made fits with two "diskbb" components, both modified by the "simpl" convolution function: $simpl \times (diskbb+diskbb)$. "Simpl" is a Comptonization model that does not provide measurements of the electron temperature nor optical depth; rather, it merely scatters a thermal distribution into a power-law and reports the fraction of the incident radiation that is scattered (Steiner et al. 2009). As with the individual (but very similar) "compTT" components, this model achieved excellent fits (see Figures 2 and 3, and Table 1). The power-law index was not well constrained in our fits, but hard indices were less favorable than relatively soft indices. After some experimentation, Γ = 3.5 (e.g. McClintock & Remillard 2006) was fixed as a representative value in our fits (see Table 1). This index is within the range observed in stellar-mass Galactic black holes in the "very high" or "steep power-law" state.

In broad terms, the relative emitting areas implied by these phenomenological patchy disk models make sense. Assuming the distance to NGC 1313 is 3.7 Mpc (Tully 1988), and assuming that the disk in NGC 1313 X-1 is viewed at an inclination of 60°, a normalization of K_{disk-1} = 16 implies a radius of $R \simeq 2100$ km (see Table 1). A flux normalization of $K_{disk-2} = 4 \times 10^{-3}$ is consistent with the values of the hotter "patches" in Table 1. This nominally corresponds to an emitting area of just $R \simeq 30$ km.

There is no a priori reason two expect a disk with patches of a single temperature. It may be more physically realistic to consider patches with many different tempratures. Therefore, we also examined how many distinct disk blackbody or simply blackbody components ae required to fit the data. The results of these fits are given in the final pairing of models in Table 1. We find that three components are sufficient to fit the data, with an inverse relationship between temperature and emitting area. (No additional hard Comptonizing component is required.)

The temperature constrast measured in all of our simple models is a factor of 7–9, whereas Dexter & Quataert (2012) considered a factor of a few. Scattering in an atmosphere and/or within the corona artificially hardens disk spectra (Merloni, Ross, & Fabian 2002). While a color correction factor of $T_{col}/T_{eff} = f_{col} = 1.7$ is canonical for accretion disks in the "high soft" state, higher correction factors are possible, and may be required in other states, particularly when a corona is present (e.g. $f_{col} \geq 3$; Merloni, Fabian, & Ross 2000). If the hot patches are more strongly distorted than the larger cool disk, the true temperature difference would be consistent with the contrast considered by Dexter & Quataert

(2012). Implied emitting areas would increase by f_{col}^2.

4. DISCUSSION AND CONCLUSIONS

Following the suggestion of patchy or inhomogeneous accretion disks in ULXs in Miller et al. (2013), we have specifically examined the ability of phenomenological descriptions of a "patchy" accretion disk (e.g. Dexter & Quataert 2012) to describe the spectra of extreme ULXs. At least in the case of NGC 1313 X-1, our fits to two epochs of joint *XMM-Newton* and *NuSTAR* spectra suggest that a patchy disk is potentially an excellent description of the observed spectra. Importantly, such models likely avoid the need for very large but cool Comptonization regions implied by recent spectral models (e.g. Gladstone et al. 2009).

Theoretical work has found evidence of photon bubble instabilities (Gammie 1998, Begelman 2001, 2002) that might naturally give rise to a patchy temperature profile and locally super-Eddington flux levels. A patchy disk need not be a unique signature of a photon bubble instability; other instabilities or mechanisms might be able to produce a similar effect. It is possible that a two–temperature or patchy disk is the natural signature of near-Eddington or super-Eddington accretion, and that a compelling correspondence between theory and observations has been identified. But, it is important to consider caveats and means of testing this scenario.

King et al. (2001) described a model for super-Eddington accretion in ULXs wherein a funnel-like geometry develops in the inner disk, mechanically beaming some radiation and foiling luminosity estimates based on isotropic emission. The hot, small region implied by our two-temperature models could correspond to the inner wall of a funnel. However, recent observations of the extreme ULX NGC 5408 X-1 have revealed X-ray flux dips typical of disks viewed at *high* inclination (e.g. Pasham & Strohmayer 2013, Grise et al. 2013). Moreover, recent radio observations of Holmberg II X-1 – which can also be fit with this spectral model – reveal three components (Cseh et al. 2014), potentially indicating a jet system viewed at high inclination. It is possible that the hot disk emission corresponds to patches rather than to a line of sight that peers into a funnel.

If ULXs are not all viewed at low inclination angles, it is possible that their radiation is nearly isotropic, and that ULXs with $L_X \geq 10^{40}$ erg s^{-1} harbor black holes with masses above the range known in Galactic X-ray binaries. This may be supported by recent evidence that cool thermal components in ULXs appear to be broadly consistent with the $L \propto T^4$ trend expected for standard thin disk accretion (Miller et al. 2013). However, this does not explain why the high energy spectra of extreme ULXs differ so markedly from stellar-mass black holes and most AGN (Bachetti et al. 2013, Walton et al. 2013a, 2014). A patchy disk model may be able to account for both spectral features.

A wider set of sources and states must be sampled in order to better test the possibility of patchy disks in ULXs. Variability below 10 keV might be ascribed to changes in the characteristic temperatures – and relative emitting areas – of cooler and hotter disk regions. Such changes might be linked to the mass accretion rate through the disk. If a mechanism like the photon bubble instability is at work, spectral variations might also be tied to changes in the disk magnetic field (which could itself be linked to the mass accretion rate). Spectral variability above approximately 10 keV might be driven partially by changes in an hotter disk component, but also changes in a corona. New observations of Holmberg IX X-1 in different states may be consistent with a patchy accretion disk model (Walton et al. 2014). It is possible that different flux ratios from the larger disk and hot patches could account for differences between very soft sources (such as NGC 5408 X-1), and harder sources (like Holmberg IX X-1).

If patchy disks power ULXs to super-Eddington luminosities, a strong wind might be driven (but see Begelman 2001). However, winds have not been conclusively detected in ULXs. Indeed, narrow absorption lines with strengths comparable to features detected in Galactic sources are ruled out at high confidence levels in deep spectra (Walton et al. 2012, 2013b; Pasham & Strohmayer 2012). Emission lines from an outflow perpendicular to the line of sight with equivalent widths comparable to SS 433 ($few \times 100$ eV; see, e.g., Marshall et al. 2013) are also ruled out. Potential low-energy lines in NGC 5408 X-1 have been discussed as having a wind origin (Middleton et al. 2014), but the lines may also be described in terms of diffuse emission with a constant flux (e.g. Miller et al. 2013).

If the disk is only super-Eddington in localized regions – the hot patches – then radiation pressure would only drive winds in localized regions. Moreover, even if the temperature profile is more shallow than the $T \propto R^{-3/4}$ derived for standard thin disks, the emission and wind regions will be concentrated close to the black hole. Any winds will therefore be highly ionized and – assuming the wind must retain some of the angular momentum of its launching point – highly smeared by rotation. Such effects would certainly inhibit the detection of a wind via *narrow* absorption lines.

It is possible that strong QPOs could be generated via a patchy disk profile. This might also cause the QPOs to be stronger at the higher energies that correspond to the hot patches; this would match observed relations in more standard X-ray binaries. QPOs are observed in some extreme ULXs (e.g. M82 X-1, NGC 5408 X-1; Strohmayer & Mushotzky 2003, Strohmayer et al. 2007). Recent simulations suggest that patchy disk profiles do not necessarily lead to QPO production (Armitage & Reynolds 2003), but additional theoretical work and observational tests may be required.

Relativistically–blurred disk reflection is the most likely explanation for the bulk of the "soft excess" observed in NLSy1s (Fabian et al. 2009, Kara et al. 2013). Yet, even in a case such as 1H 0707–495 – wherein the disk reflection spectrum is particularly strong and clear – a very soft blackbody component is still required at the edge of the band pass (Fabian et al. 2009). It is possible that this emission represents the high energy tail of a patchy accetion disk that puts out more power in its lower–temperature UV/EUV component. It is interesting to note that some sources identified by Greene & Ho (2007) appear to have similar X-ray spectra, and "slim" or super-Eddington disk models may apply in some cases.

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TABLE 1
EXAMPLE PHENOMENOLOGICAL PATCHY DISK MODELS

Epoch	N_H (10^{21} cm^{-2})	kT_{disk-1} (keV)	K_{disk-1}	kT_{disk-2} (keV)	K_{disk-2} (10^{-3})	kT_e (keV)	τ	$K_{comptt-1}$ (10^{-6})	$K_{comptt-2}$ (10^{-7})	χ^2/ν
1	2.4(1)	0.375(5)	4.7(3)	2.64(5)	2.8(1)	–	–	–	–	2032/1878
2	2.4(1)	0.376(6)	4.8(4)	2.61(4)	3.1(2)	–	–	–	–	2064/1935
1	2.73(7)	0.27(2)	17(4)	2.4(2)	3(1)	100*	0.1*	5(1)	4(2)	1917/1876
2	0.265(7)	0.27(2)	15(3)	2.3(2)	4(1)	100*	0.1*	4(1)	5(2)	1939/1933
	N_H (10^{21} cm^{-2})	kT_{disk-1} (keV)	K_{disk-1}	kT_{disk-2} (keV)	K_{disk-2} (10^{-3})			Γ	f_{scat}	χ^2/ν
1	2.7(1)	0.28(1)	16(3)	2.30(6)	4.0(4)			3.5*	0.42(5)	1937/1877
2	2.7(1)	0.28(1)	16(3)	2.23(5)	4.6(4)			3.5*	0.42(5)	1954/1934
	N_H (10^{21} cm^{-2})	kT_{disk-1} (keV)	K_{disk-1}	kT_{disk-2} (keV)	K_{disk-2} (10^{-2})	kT_{disk-3} (keV)	K_{disk-3} (10^{-4})			χ^2/ν
1	2.6(1)	0.33(1)	7.9(9)	1.5(2)	1.1(3)	4.1(4)	4(1)			1923/1876
2	2.6(1)	0.33(1)	7.8(9)	1.6(2)	0.9(1)	4.2(5)	3(2)			1942/1933

NOTE. — The table above lists values obtained from spectral fits to two epochs of joint *XMM-Newton* and *NuSTAR* observations of NGC 1313 X-1. The first pairing of models consist of only two simple “diskbb” components. The second pairing adds Comptonization components via “compTT”. More realisitic fits to better data might require different electron temperatures and optical depths for each “compTT” component; however, a broad range of combinations give acceptable fits to these spectra. Values of kT_e = 100 keV and τ = 0.1 were selected to demonstrate that standard Comptonization is compatible with the data. The flux normalizations of the “compTT” components floated independently. The third pairing attempts to model potential Comptonization via “simpl”, which acted on both disk components together. The power-law index in the model was poorly constrained but required to be fairly steep. A value of Γ = 3.5 was selected as it gives excellent fits and is commensurate with the “very high” or “steep power-law” states observed in standard black hole X-ray binaries. The bottom pairing consists of models with three disk blackbody components, with no Comptonization. Three simple blackbody components give equally good fits and approximately the same temperatures.

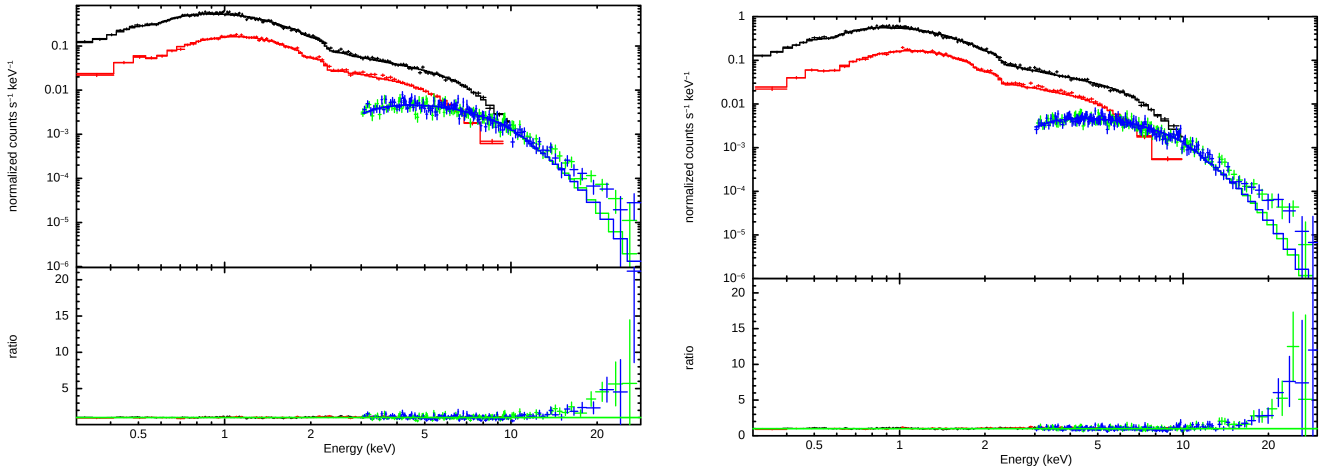

FIG. 1.— The *XMM-Newton* EPIC-pn (black), EPIC-MOS2 (red), and *NuSTAR* FPMA (green) and FPMB (blue) spectra of NGC 1313 X-1 are shown here. Spectra from Epochs 1 and 2 are shown in the left and right panels, respectively, with a toy model for a "patchy" disk (*diskbb*+*diskbb*, see Table 1). This simple model provides a relatively good fit ($\chi^2/\nu \simeq 1.07$) in that it accounts for the bulk of the spectrum. However, it fails at high energy, likely due to unmodeled Comptonization.

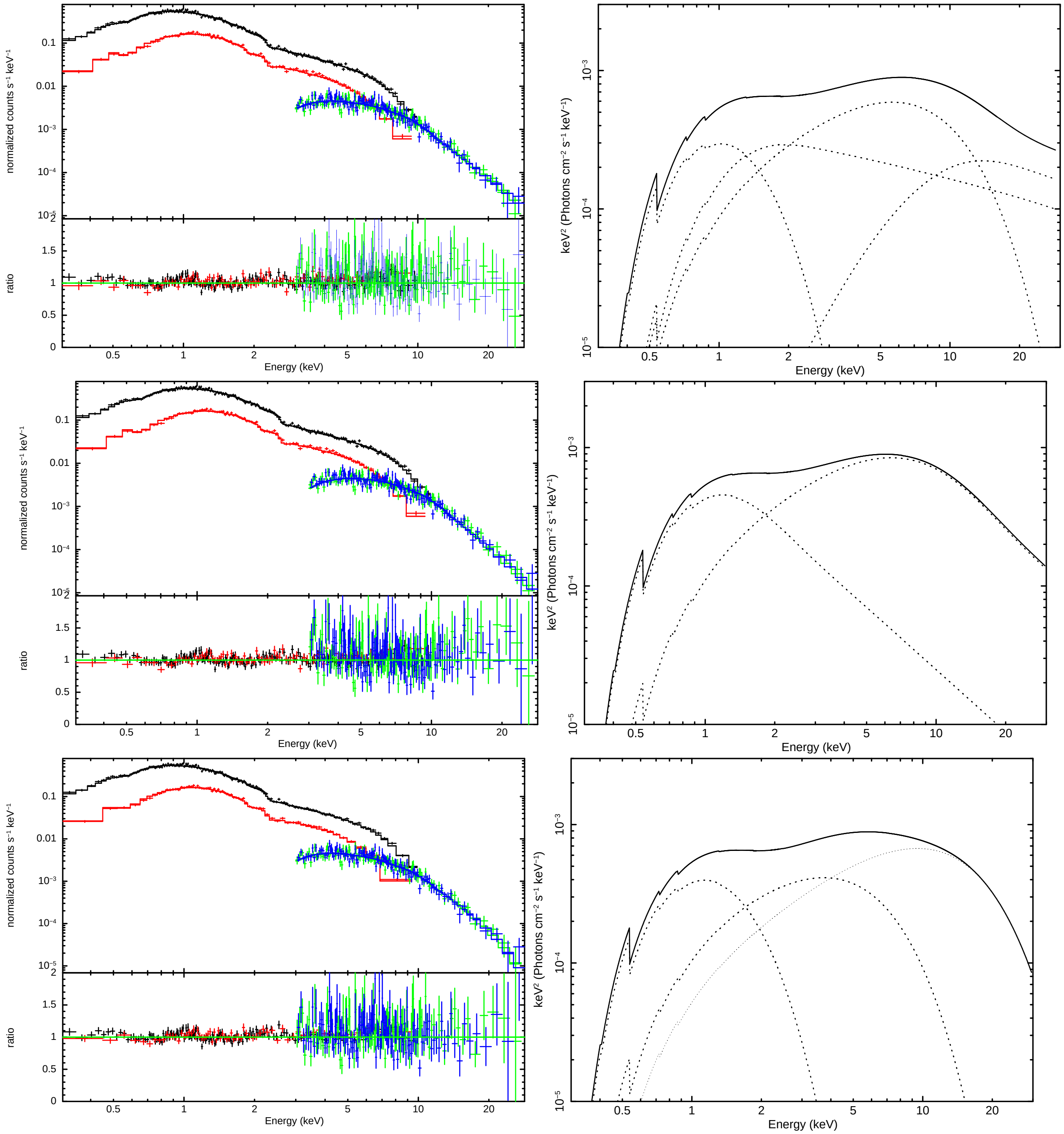

FIG. 2.— *XMM-Newton* EPIC-pn (black), EPIC-MOS2 (red), and *NuSTAR* FPMA (green) and FPMB (blue) spectra of NGC 1313 X-1 from Epoch 1 are shown here in the lefthand panels. The righthand panels show the corresponding model, without the data. In the top panels, two "diskbb" components were used to simulate a "patchy" disk, modified by Comptonization via "compTT". In the middle panels, the "compTT" components were replaced by the "simpl" convolution model. In the bottom panels, three disk blackbody components were fit, without Comptonization. Simple blackbody modela are also effective. All of these simple models yield excellent fits (see Table 1).

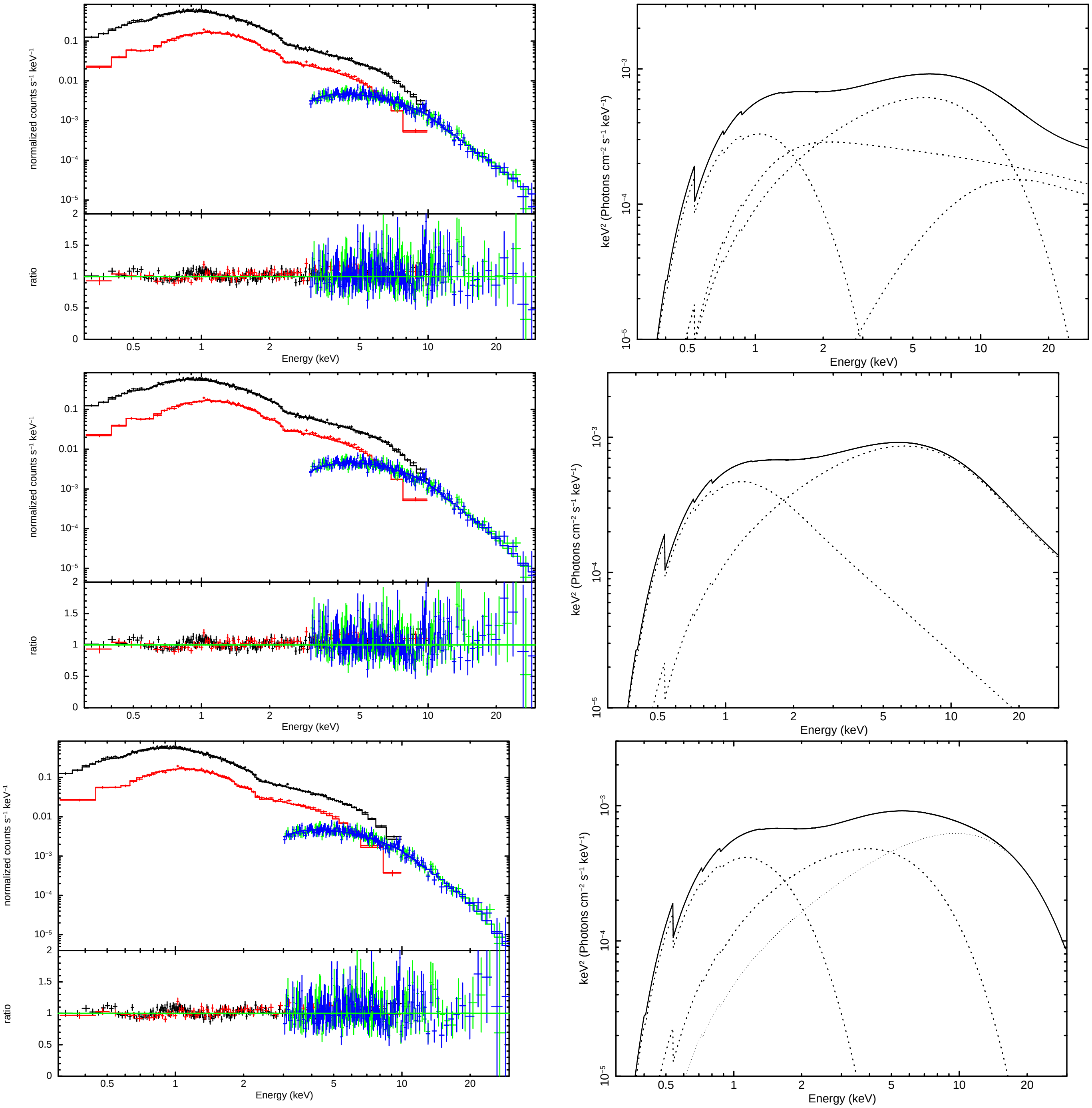

FIG. 3.— *XMM-Newton* EPIC-pn (black), EPIC-MOS2 (red), and *NuSTAR* FPMA (green) and FPMB (blue) spectra of NGC 1313 X-1 from Epoch 2 are shown here in the lefthand panels. The righthand panels show the corresponding model, without the data. In the top panels, two "diskbb" components were used to simulate a "patchy" disk, modified by Comptonization via "compTT". In the middle panels, the "compTT" components were replaced by the "simpl" convolution model. In the bottom panels, three disk blackbody components were fit, without Comptonization. Simple blackbody modela are also effective. All of these simple models yield excellent fits (see Table 1).