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Space Telescope and Optical Reverberation Mapping Project. VII. Understanding the UV anomaly in NGC 5548 with X-Ray Spectroscopy

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ABSTRACT

During the Space Telescope and Optical Reverberation Mapping Project (STORM) observations of NGC 5548, the continuum and emission-line variability became decorrelated during the second half of the 6-month long observing campaign. Here we present *Swift* and *Chandra* X-ray spectra of NGC 5548 obtained as a part of the campaign. The *Swift* spectra show that excess flux (relative to a power-law continuum) in the soft X-ray band appears before the start of the anomalous emission-line behavior, peaks during the period of the anomaly, and then declines. This is a model-independent result suggesting that the soft excess is related to the anomaly. We divide the *Swift* data into on- and off-anomaly spectra to characterize the soft excess via spectral fitting. The cause of the spectral differences is likely due to a change in the intrinsic spectrum rather than being due to variable obscuration or partial covering. The *Chandra* spectra have lower signal-to-noise ratios, but are consistent with *Swift* data. Our preferred model of the soft excess is emission from an optically thick, warm Comptonizing corona, the effective optical depth of which increases during the anomaly. This model

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simultaneously explains all the three observations: the UV emission line flux decrease, the soft-excess increase, and the emission line anomaly.

Subject headings: galaxies: active – galaxies: broad line region – galaxies: individual (NGC 5548)– galaxies: X-ray

1. Introduction

The Space Telescope and Optical Reverberation Mapping (STORM) project intensively monitored the well-known active galactic nucleus (AGN) NGC 5548. As a part of this project, NGC 5548 was observed with the *Hubble Space Telescope* (*HST*) in 2014 for 180 days with daily cadence, obtaining 171 usable epochs. The source was also monitored with *Swift* and in the optical with ground-based observations. We also observed the source with *Chandra* four times during the HST observing campaign. The goal of the STORM project was to perform velocity-resolved reverberation mapping (RM) of the optical and UV emission lines with fine time sampling, long duration, and high S/N spectra. The multiwavelength continuum observations were performed to probe the structure of the accretion disk and to track changes in the ionizing continuum of the source.

The *HST* (UV), *Swift* (X-ray), and ground-based (optical) continuum and spectroscopic observations are presented in Papers I–V (De Rosa et al. 2015, Edelson et al. 2015, Fausnaugh et al. 2016, Goad et al. 2016, and Pei et al. 2017, respectively). Reverberating-disk models for NGC 5548 are presented in Paper VI (Starkey et al. 2017). As noted in Paper I and discussed in detail in Paper IV (Goad et al. 2016), an anomalous behavior of the broad ultraviolet emission lines was observed during the campaign. For most of the campaign, the broad UV emission lines responded to changes in the UV continuum, as generally expected for broad-line reverberation. However, there was a period of 60–70 days during the latter half of the campaign when the UV lines did not reverberate with the UV continuum. This was also accompanied by a significant drop in the fluxes of UV emission lines.

Such an "anomaly", when the continuum and emission-line variability became decoupled, was not previously observed in RM campaigns and demands explanation. Moreover, understanding the origin of the anomaly is critical to the robustness of reverberation mapping technique, since it depends on the observed continuum flux being a good proxy for the unobserved EUV ionizing continuum. Here we present X-ray spectra obtained as a part of AGN STORM that provide important clues as to the origin of the anomaly. In §2 we present analysis of *Swift* spectra. The *Chandra* observations and spectral analysis are presented in §3. In §4 we discuss how the appearance of a soft-X-ray excess a few days before the anomaly may clarify its origin. Although NGC 5548 was observed intensively with *XMM-Newton* in the years prior to the AGN STORM campaign (Kaastra et al. 2014; Mehdipour et al. 2015, 2016, Cappi et al. 2016), a detailed comparison with these data is beyond the scope of this paper. Here we focus on *Swift* and *Chandra* data obtained during our campaign.

2. *Swift* Observations

2.1. Spectra and Analysis

The description of the *Swift* observations, data reduction, and time series analysis are presented in Paper II. Here we present a time-resolved spectral analysis. In Figure 1, we show the 0.3–10.0 keV spectra in 9 time bins, from pre-anomaly (days 1–54) to post-anomaly (days 150–170). The exposure times for each period are given in Table 1. We see that the hard X-ray continuum (2–10.0 keV) is constant over the period of the observation, but the soft X-ray flux (below ≈ 0.8 keV) increases from the pre-anomaly period (days 1–54) to days 55–75, peaks during days 75–85, then fades during days 85–100, with the latter spectra being broadly consistent with the pre-anomaly spectra. This is a model-independent result, suggesting that the soft excess is likely related to the anomaly.

In order to perform the spectral modeling and to quantify the soft excess, we divided the *Swift* observations into two parts, which we call pre-anomaly and anomaly spectra (days 0.4 to 54.5 $=$ JD 2456690.4189 to 2456744.5088 and days 55.4 to 84.9 $=$ JD 2456745.3676 to 2456774.9165, respectively). A Galactic column density of $N_H = 1.69 \times 10^{20}$ cm^{-2} (Dickey & Lockman 1990) was included in all the models. We simultaneously fitted both the spectra with an absorbed power-law model, adding a blackbody (BB) component to parameterize the soft excess. The parameters of the power-law, slope (photon index Γ) and normalization, were tied for the two spectra (as justified by Fig. 1), but the intrinsic absorption and BB parameters were allowed to vary. The fit showed that the BB temperature is the same in the two spectra, so we tied the temperature and fitted the spectra again. The resulting fit was good ($\chi^2_\nu = 1.16$ for 1001 degrees of freedom).

In their model of the entire *XMM-Newton* observing campaign, Cappi et al. (2016) found an additional scattered soft X-ray component dominated by narrow emission lines, with 8% of the total soft X-ray flux. This soft component was constant over the whole campaign, so cannot be responsible for the variable soft-excess we see here. Nonetheless, we added a similar component to our model (XSPEC model **apec**) with flux as in Cappi et al. (2016) and found no improvement to the fit ($\chi^2_\nu = 1.16$ for 1001 degrees of freedom). The best fit spectra are shown in Figure 2 and the model parameters are given in Table 2 along with the flux in the soft-excess after correcting for absorption. The soft excess is significantly stronger in the anomaly spectrum. The intrinsic spectrum (without the instrument response) is shown in the bottom panel of Figure 2; the absorbed power-law, BB, and the scattered emission-line components are shown as dotted lines.

While a BB component described the soft excess well, “warm Comptonization”, in which seed photons from the accretion disk are Compton up-scattered by an optically thick hotter corona is likely a more realistic model. Thus we also tried to fit the soft excess with a warm Comptonization model (**compTT** in XSPEC), together with an absorbed power-law. We fixed the model parameters (seed photon temperature, corona temperature and optical depth) to the parameters in Medhipour et al. (2015), allowing only the normalization to vary between the pre-anomaly and anomaly spectra. The resulting fit was worse ($\chi^2_\nu = 1.33$ for 1015 degrees of freedom; $\Delta\chi^2 = 189$ compared to the BB fit) and significant negative residuals were observed below 1 keV; in particular the warm Comptonization model did not adequately fit the spectral turnover below 0.5 keV. We could improve the fit by adding another cold absorber at the source (best fit $N_H = (4.7 \pm 0.7) \times 10^{20}$ cm^{-2}), resulting in $\chi^2_\nu = 1.2$ for 1014 degrees of freedom. Thus, if warm Comptonization is the correct description of the soft excess, it will have to lie behind this absorbing medium. The best fit normalizations are given in Table 3 and the fit is shown in Figure 3; as expected the normalization is significantly higher during the anomaly. Alternatively, the change in soft-excess could be a result of changing optical depth of the corona, as shown in Page et al. (2004). We therefore fixed the normalization to the pre-anomaly value and allowed only optical depth to vary. As expected, we find significantly higher optical depth during the anomaly (Table 3). A warm Comptonized corona with variable optical depth is our preferred model for reasons discussed in §4.2.

2.2. Alternative models

It is possible that the observed spectral shape (the “soft excess”) is an artifact of a partially covering cold absorber. We therefore tried to fit the soft excess with a partial covering power-law model. The best-fit absorption column densities in the two spectra were found to be the same within the errors, so we refitted the two spectra after tying the column densities. As expected, the absorber covered the continuum source more during the pre-anomaly period (covering fraction 0.91 ± 0.01) and less during the anomaly (covering fraction 0.75 ± 0.02). However, this fit is worse ($\chi^2_\nu = 1.4$ for 1003 degrees of freedom) than the BB model, with obvious residuals in the soft X-ray spectrum. As seen in Fig.4, the partial covering absorber model does not adequately account for the excess flux in the soft X-ray band in the anomaly spectrum, or the spectral turnover below ≈ 2 keV. Thus the *dominant* parameter describing the change in soft excess between pre-anomaly and anomaly spectra cannot be the covering factor.

Alternatively, the apparent soft “excess” could result from the recovery of the soft X-ray spectrum through a warm absorber. NGC 5548 is known to have an X-ray warm absorber, detected even in low-resolution spectra (e.g. Nandra et al. 1993; Mathur et al. 1995). We therefore tried to fit the *Swift* spectra with an absorbed power-law model modified by a warm absorber. We used PHASE (Krongold et al. 2003) to model the warm absorber. The parameters of this model are ionization parameter U, total column density $N_{\rm H}$, velocity v, and the microturbulent velocity σ. Given the low resolution of the spectrum, we fixed v to match the galaxy redshift and σ was fixed to 200 km s^{-1}. Thus the free parameters of the warm absorber model were U and $N_{\rm H}$. Once again, we fitted the two spectra simultaneously, keeping the power-law parameters tied. The fit was good ($\chi^2_\nu = 1.1$ for 1003 degrees of freedom) and the results of this fit are given in Table 4. The absorber $N_{\rm H}$ was found to be similar in the two spectra, and as expected, the warm absorber in the anomaly spectrum is more ionized (higher U), leading to the apparent excess in the soft X-ray band. The warm absorber column density, however, is unusually large (about $\log N_{\rm H}({\rm cm}^{-2}) = 22.2$). The warm absorber column density in NGC 5548 have varied from about $\log N_{\rm H}({\rm cm}^{-2}) = 20.3$ to $\log N_{\rm H}({\rm cm}^{-2}) = 21.7$ (Mehdipour et al. 2015). While a significant increase in the column density is possible, it is also possible that the column density is actually lower, and there is an additional soft-excess component; we cannot distinguish between these two models. Warm absorbers with low ionization parameter are clearly related to UV absorption lines (e.g. Mathur et al. 1994,1995,1998; Monier et al. 2001; Krongold et al. 2003,2005,2007; Kaspi et al. 2004), so variability of the UV absorber (Kriss et al. in prep.) may help distinguish between the two possibilities. As noted below in §4.2, the warm absorber model alone cannot explain the anomaly, so a variable warm absorber is unlikely to be the correct model of the soft excess.

As noted in §1, NGC 5548 was monitored intensively with *XMM-Newton* in 2013–2014. The source appeared in a highly obscured state then (Kaastra et al. 2014), with a column density of $\approx 10^{23}$ cm^{-2}. In our STORM campaign, the absorption column density was over an order of magnitude lower ($\approx 10^{22}$ cm^{-2}). A detail spectral analysis of *XMM-Newton* observations of NGC 5548 is presented in Cappi et al. (2015) who modeled the spectra with six different components: a power-law continuum; a cold reflection component; a soft thermal Comptonization emission model; a scattered emission-line component; a warm absorber; and up to two high column density partial covering "obscurers". Given the S/N of our *Swift* observations, it is not possible to fit the spectra with such a complex model and deduce meaningful information. Moreover, our interest is to understand the *difference* between the pre-anomaly and anomaly spectra. It is possible that the observed changes in the soft excess are caused by a combination of changes in multiple components. We cannot constrain these multiple components; instead we have looked for a dominant model that describes the soft excess variability. During the *XMM-Newton* campaign, the dominant variability component in the 0.3–0.8 keV range of soft excess was the covering fraction of the obscurer as reported in Mehdipour et al. (2016), but Cappi et al. (2015) show that the normalization of the Comptonization component was also important. In our STORM campaign, the soft excess can be modeled as a black body, a warm absorber, a warm Comptonizing medium behind a thin veil of matter or a combination of all these models; the *Swift* spectra cannot discriminate among these models. However, the dominant variability is *not* caused by the covering fraction of an absorber. As we discuss further in §4, the warm Comptonization model naturally explains several aspects of the UV anomaly, so this is our preferred model. While a change in the normalization of the warm Comptonization model can adequately describe the spectral difference between the pre-anomaly and anomaly spectra, our preferred model is of the change in the effective optical depth (§4). Thus we see that the *shape* of the X-ray continuum changed during the anomaly phase, not just the normalization; this was clear from the model independent spectra shown in Fig. 1, and the spectral modeling confirms the same. Recently Gardner & Done (2017) studied optical/UV variability of NGC 5548 and argued that a soft excess is required to understand the observed continuum lags; the observation of a soft excess with *Swift* and *Chandra* (§3) are consistent with this expectation.

3. *Chandra* Observations and Analysis

As a part of the *HST* campaign, we also observed NGC 5548 with the *Chandra* Low Energy Transmission Grating (LETG) and ACIS-S on four occasions from Feb 2014 to June 2014 for 5 ks each. The observation details are given in Table 5. The LETG was placed in front of the detector to avoid pile-up; obtaining high resolution grating spectra was not the goal of these short 5 ks exposures. We analyzed the data using standard CIAO tools (version 4.7 and *caldb* version 4.6.7). We reprocessed all the observations using the *Chandra repro* task, which results in enhanced data quality and better calibration. We extracted the zeroth-order source and background spectra using the CIAO tool *specextract*, which also builds proper response (RMFs) and effective area (ARF) files required for analysis. We analyzed the spectra using both *XSPEC* and the CIAO fitting package *Sherpa*. We binned the spectra to 25 counts minimum per channel using *ftool grppha*.

It was clear that in the hard X-ray band (2–8 keV) the spectra are very similar, but at softer energies they show differences, similar to what we found in *Swift* spectra. Thus we fit the *Chandra* spectra with an absorbed power-law model, as we did for *Swift* spectra, with the results shown in Figure 5. Once again we see that there is a clear soft excess in *Chandra* observations II (day $57 =$ JD 2456747) and III (day $93 =$ JD 2456784), which were taken during the anomaly. Observations I and IV took place when the source was in its normal state, and they show no soft excess. The appearance of the soft excess in observations II and III once again suggests that it may be related to the anomaly.

We fit the *Chandra* spectra with the same series of models discussed above, primarily to determine if they are consistent with the *Swift* results despite their lower S/N. The models which fit the *Swift* data well also fit the the *Chandra* data well, and the partial covering power-law model also is a poor model of the *Chandra* spectra ($\chi^2_\nu = 2.32$ for $\nu = 63$ degrees of freedom), with the fit yielding a covering fraction of one.

4. Results

4.1. Soft-Excess

Ever since the discovery of soft X-ray excesses (Singh et al. 1985; Arnaud et al. 1995), there has been a debate about their origin and physical nature. The possible explanations have narrowed down to (1) reflection of the hard X-ray source by the accretion disk (e.g. Crummy et al. 2006); (2) an additional Comptonizing medium around the accretion disk (e.g. Ross et al. 1992); or (3) thermal emission from an accretion disk. Understanding the nature of the soft excess is important because of its potentially large luminosity and because it is an integral part of the accretion process. Though no correlation has been found between the strength of the soft-excess and the black hole mass or its luminosity (e.g. Bianchi et al. 2009), multiwavelength studies have revealed a possible correlation of the UV slope with the soft excess strength and shape (e.g. Walter & Fink 1993; Atlee & Mathur 2009). From the multi-wavelength campaign studying Mrk 509, Mehdipour et al. (2011) found that the soft X-ray excess is correlated with the thermal optical-UV emission from the accretion disk and is not correlated with the 2–10 keV X-ray power-law. This favors Comptonization of UV/optical photons by a hot plasma for the origin of the soft excess.

In NGC 5548, the soft excess was previously detected in 2000 during an unobscured period, but the source was heavily absorbed during 2013 (Kaastra et al. 2014) and the soft-excess was modeled as a Comptonized corona (Mehdipour et al. 2015). The soft excess observed during our campaign is well-modeled as a black-body (an optically thick corona would emit like a black body), but the anomaly is better explained by the warm Comptonization model, as discussed below, so this is our preferred explanation.

4.2. Understanding the UV anomaly

The X-ray spectra provide a possible explanation for the UV anomaly. First, the X-ray spectra rule out variable absorption as the cause of the anomaly. If anything, the absorption was lower during the anomaly. It is possible that the EUV ionizing continuum source was obscured, while the X-ray source was not, but that is unlikely since the X-ray continuum source size in AGNs appears to be smaller than that of the UV/EUV (e.g. Mosquera et al. 2013). Partial covering of the continuum fit the data poorly and thus are unlikely to be the cause of the anomaly.

The second important fact is that the UV emission line flux decreased during the anomaly. This suggests that the EUV ionizing continuum flux decreased during the anomaly (as discussed in Paper IV; the ionization potential of C III is 47.9 eV and that of Si III is 33.5 eV). This cannot be explained by a change in the warm absorber because the warm absorber in the anomaly spectrum is more ionized (higher U), requiring an increase in the EUV continuum during the anomaly. Thus our preferred scenario is that of the intrinsic change in the soft X-ray spectrum.

The observed changes can be naturally explained by the warm Comptonization model. In this model, the UV disk photons are Compton up-scattered to soft X-ray energies by the optically thick corona. In a normal situation, where the UV and soft X-ray fluxes are correlated, higher UV flux leads to more input photons for Comptonization, so more soft X-rays; we can describe this as a change in the normalization of the model. What we have, however, is the opposite situation during the anomaly: the EUV flux decreases, while the soft X-ray flux increases. This can be understood as follows: the EUV photons are depleted from the flux we see, but are Comptonized into soft X-rays. This could be due to either a true change in the optical depth or an increase in the region covering the UV/EUV emitting region, which could be considered an increase in the "effective optical depth" of the corona. The BLR is then deprived of the ionizing photons, so the emission-line and UV continuum variability are decoupled (the "anomaly"). The increase in the effective optical depth in the anomaly spectrum is $\Delta\tau = 1.8$, implying a factor of $e^{-\Delta\tau} = 1/6$ reduction in the EUV flux. Interestingly, the observed UV emission line flux drop during the anomaly is also about a factor of $1/6 = 16.5\%$ (Figure 1 in Paper IV shows the flux drop to be between 15% and 20%). Thus the warm Comptonization model can simultaneously explain all the three observations (the UV emission line flux decrease, the soft-excess increase, and the emission line anomaly), so it is our preferred model. We do not understand why the corona may change its physical structure in this way; observations such as these provide motivations for further theoretical work on the structure of the accretion disk and the corona. Notably, an anomalous continuum behavior has been seen before. In 3C273, there was one epoch of *XMM-Newton* observations when the UV flux decreased but the X-ray flux increased (Page et al. 2004), while the source otherwise behaved normally.

5. Conclusion

In this paper we report on analyses of *Swift* and *Chandra* X-ray spectra taken during the *HST* monitoring campaign of NGC 5548 that help us understand the UV anomaly reported in Paper IV. We show that obscuration of the continuum source is unlikely to be the cause of the anomaly. Instead, the spectral energy distribution of the continuum changed during the anomaly, as seen in the X-ray spectra. A possible scenario may be that the warm Comptonizing corona covered more of the accretion disk during the anomaly, depleting EUV photons while increasing the soft excess. The decrease in the ionizing continuum then leads to the emission-line anomaly. In order to understand the finer details of the anomaly, detailed photoionization models will be necessary. These results demonstrate the importance of contemporaneous X-ray spectra to interpreting high quality RM data. We suggest that future reverberation mapping campaigns in the optical and/or UV include an X-ray component as well.

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Table 1: *Swift* exposure times

Days	Julian dates	Exposure Time (ks)
0–55	2456690.4189 – 2456744.5088	58
55–75	2456745.3676 - 2456764.7642	32
75–85	2456765.6905 - 2456775.5760	7
85–100	2456776.0284 - 2456790.6312	20
100–110	2456791.0273 - 2456800.3587	12
110–120	2456800.8177 - 2456810.5546	14
120–135	2456810.8812 - 2456825.5525	10
135–150	2456825.9454 - 2456840.2837	16
150–170	2456840.2768 - 2456859.7580	15

Table 2: Fits to *Swift* spectra: absorbed power-law plus black body model[1]

Obs ID	BB $(KT)^2$ keV	BB Norm 10^{-5} ph keV^{-1} s^{-1} cm^{-2}	BB flux 0.1–2keV 10^{-12} ergs cm^{-2} s^{-1}	Intrinsic Absorption $N_H 10^{22}$ cm^{-2}	Photon Index[2] Γ	Powerlaw Norm[2] 10^{-3} ph keV^{-1} s^{-1} cm^{-2}
Anomaly	0.12 ± 0.005	4.5 ± 0.2	3.7	0.66 ± 0.05	1.49 ± 0.04	5.9 ± 0.3
Pre-anomaly	0.12 ± 0.005	1.7 ± 0.1	1.4	1.13 ± 0.06	1.49 ± 0.04	5.9 ± 0.3

1. A scattered component is also included in the fit (see text)
2. Powerlaw parameters and BB temperature are tied for both the datasets.
3. χ^2_ν for the joint fit is 1.16 for $\nu = 1001$ dof..

Table 3: *Swift* spectra: Warm Comptonization fit parameters[1,2]

Spectrum	Optical depth	Normalization
Anomaly	22.34 ± 0.16	50.34 ± 1.85
Pre-anomaly	20.55 ± 0.15	22.09 ± 0.94

1. Powerlaw parameters are tied for both the datasets.
2. The warm corona temperature was fixed at 0.15 keV and the seed photon temperature to 0.74 eV. Only one parameter (optical depth or normalization) was allowed to vary at a time.

Table 4: *Swift* spectra: PHASE fit parameters

Spectrum	Log(U)	Log(N_H/cm^{-2})	Photon index[1] Γ
Anomaly	-0.3 ± 0.03	22.12 ± 0.01	1.42 ± 0.02
Pre-anomaly	-0.4 ± 0.01	22.18 ± 0.01	1.42 ± 0.02

1. Powerlaw parameters are tied for both the datasets.
2. χ^2_ν for the joint fit is 1.1 for $\nu = 1003$ dof.

Table 5: NGC 5548 Chandra Observation Log.

Obs.	ID	Date of Observation	JD	Exposure Time
I	15659	2014, Feb 3	2456692 (pre-anomaly)	5 ks
II	15660	2014, Mar 30	2456747 (just before anomaly)	5 ks
III	15661	2014, May 6	2456784 (during anomaly)	5 ks
IV	15662	2014, Jun 23	2456832 (post-anomaly)	5 ks

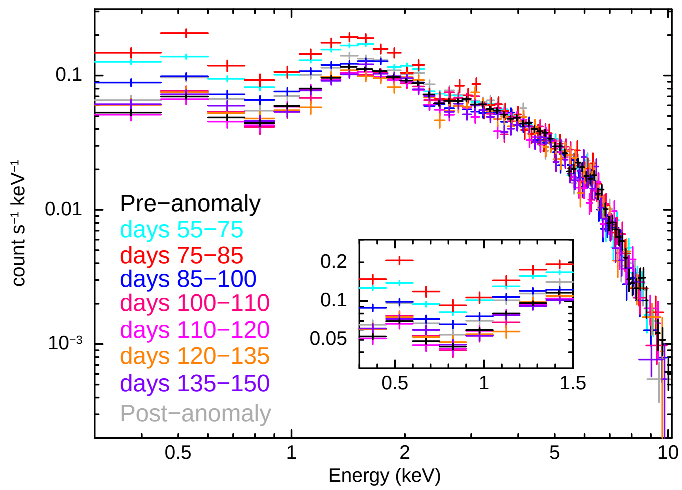

Fig. 1.— *Swift* spectra in different time bins. Note the increase in the soft excess from the pre-anomaly phase, peaking at days 75–85 (red) and then decreasing. This is a model-independent result, and suggests that the change in the spectral energy distribution in NGC 5548 is responsible for the anomaly. The inset shows 0.3 to 1.5 keV spectra for clarity.

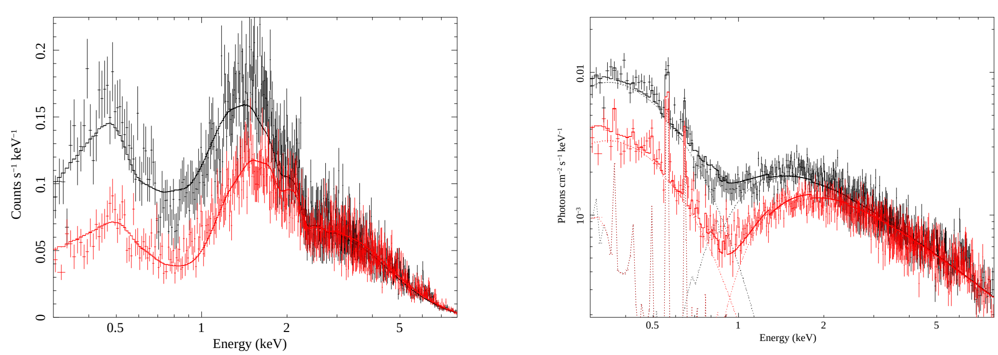

Fig. 2.— *Top: Swift* spectra: anomaly (black) and pre-anomaly (red) fit with an absorbed power-law plus a black-body model. An additional scattered component is also included. *Bottom:* The intrinsic spectra (without folding in the instrument response); the three model components are shown as dotted lines.

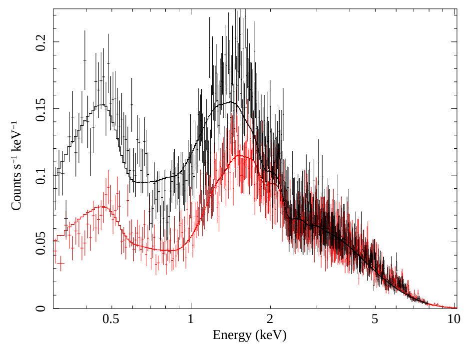

Fig. 3.— As in Fig. 2, but fit with a warm Comptonization model.

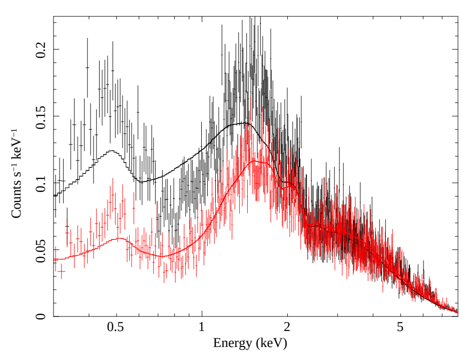

Fig. 4.— The *Swift* spectra fitted with a partial covering absorber model. This is clearly a poor fit compared to the models shown in Fig. 2 and 3.

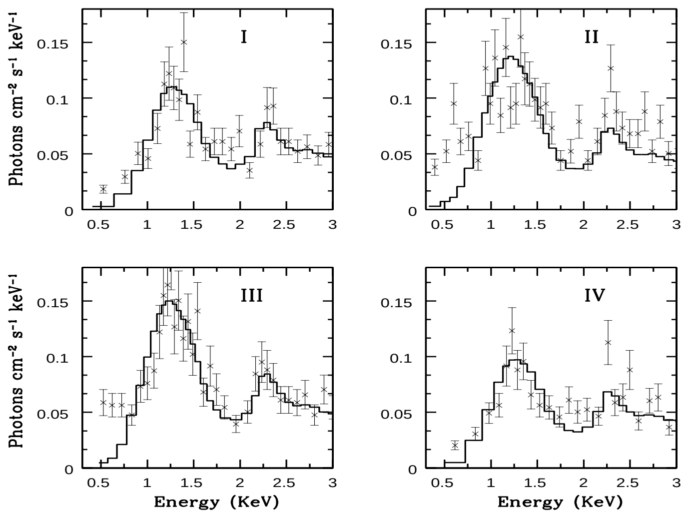

Fig. 5.— *Chandra* spectra with the best fit absorbed powerlaw model. The soft excess is apparent in observations II and III.

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